The WRP Notebook

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Wetlands Dynamic Water Budget Model

PURPOSE: The hydraulic and hydrologic characteristics of a wetland influence all wetland functions, and consequently are of primary importance in evaluating these functions. The processes by which water is introduced to, temporarily stored in, and removed from a wetland are commonly known as the water budget. A Wetlands Dynamic Water Budget Model (WDWBM) has been developed through the Wetlands Research Program (WRP) at the U.S. Army Engineer Waterways Experiment Station to predict the interaction of surface water, groundwater, and vertical transport processes within wetlands (Walton and others 1995).

The model has been designed to simulate the major components of the hydrologic cycle, which include meteorological input, canopy interception, overland flow, channel routing, infiltration, saturated groundwater flow, evapotranspiration, and upstream watershed inflows (Figure 1). This technical note describes the features of the WDWBM.

MODEL STRUCTURE: The WDWBM is a coupled surface/aquifer simulation program that computes the dynamic movement of water through various types of watersheds, such as wetlands. The model has three modules (Figure 2), which predict surface water flow, vertical processes, and horizontal groundwater flow. Emphasizing efficiency and ease of use, the model uses an explicit quasi-three-dimensional link-node structure.

Input is organized into files containing information required by each of the modules. Output consists of files containing water surface elevations, flows, velocities, groundwater heads, and volume balances. An interactive PC tutorial is available to help the user identify data sources, prepare input data files, execute and calibrate the model, and select output options. A postprocessing program is available to model the output for graphical display.

SURFACE WATER MODULE: The surface water module was designed to simulate channel and overbank flows, tidal forcing, river inflows, upstream basin flows, wind shear, flooding and drying, various bottom friction formulations, and hydraulic structures such as culverts, weirs, and gates.

The module is based on a quasi-two-dimensional, link-node model structure (Figure 3), which has been successfully applied to the Bolsa Chica wetlands in California (Hales and others 1990), and the Black Swamp of the Cache River (Walton and others 1995). A momentum equation (the dynamic wave equation, the diffusion wave equation, or an equation for a hydraulic structure) is solved along each link, and volume conservation is enforced at each node to compute stage.

A variety of boundary conditions can be applied, including a prescribed stage hydrograph, prescribed flow hydrograph, loop rating curve, specified rating curve, and inflows from upstream basins.

VERTICAL PROCESSES MODULE: The processes simulated in the vertical module are canopy interception, canopy evaporation, surface water evaporation, soil water evaporation, transpiration, and infiltration. The vertical module is based on the HELP model (Schroeder and others 1988) and the SPUR model (Wright and Skiles 1987) and solves a series of one-dimensional, vertical flow equations.

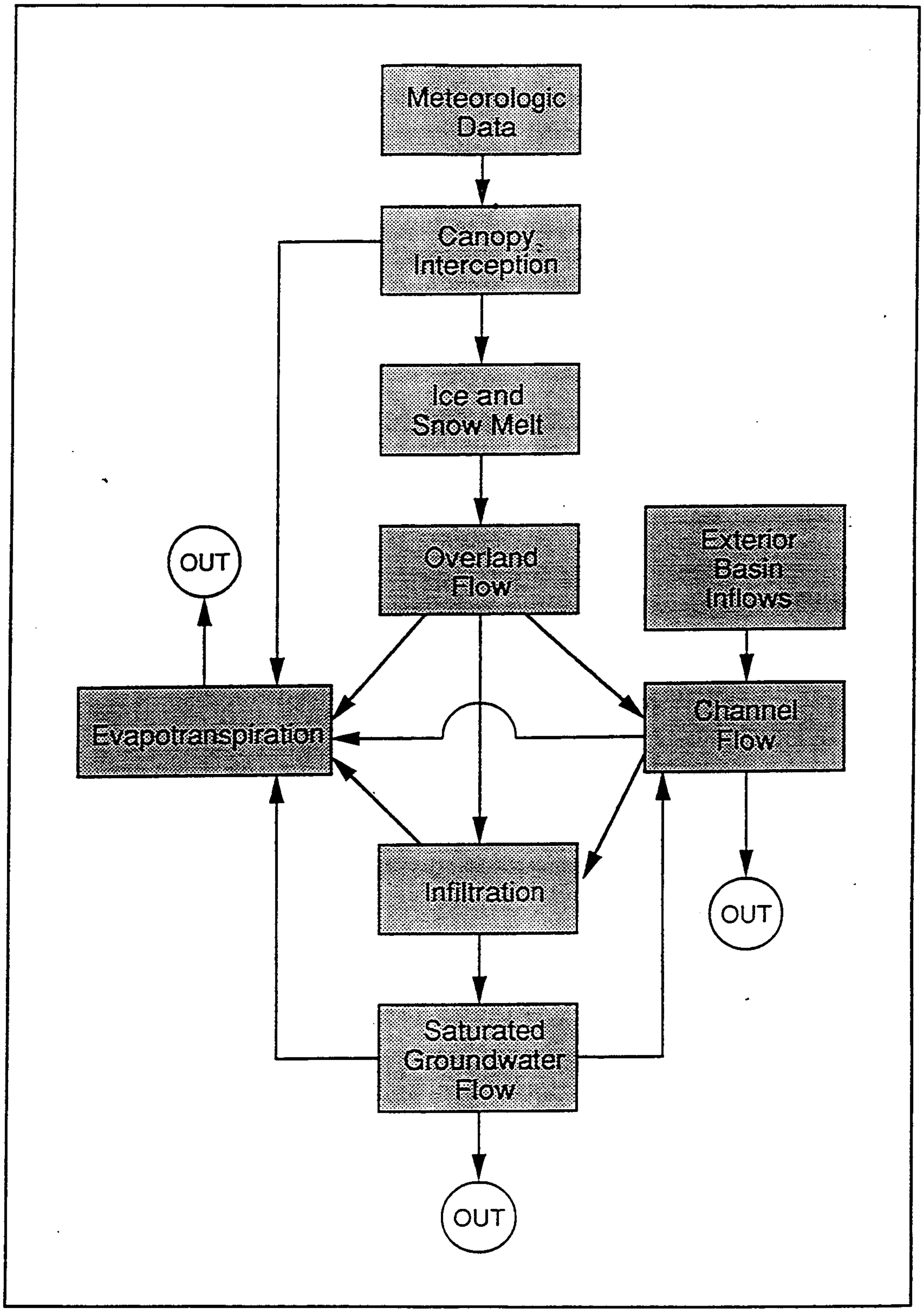

Figure 1. Schematic processes

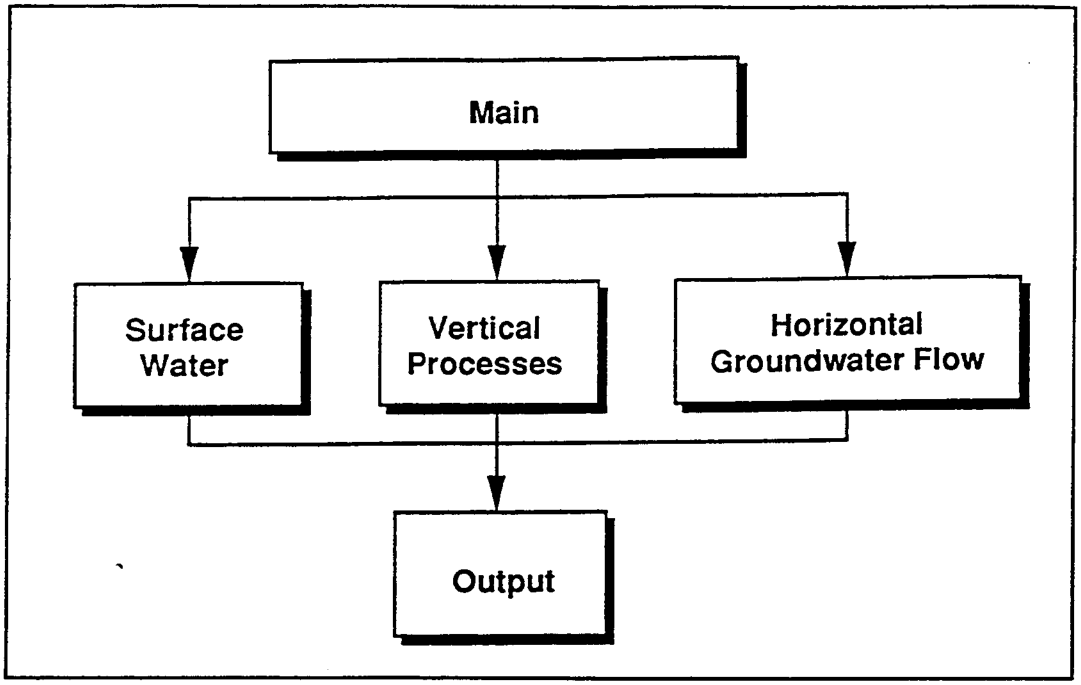

Figure 2. Three modules of Wetlands Dynamic Water Budget Model

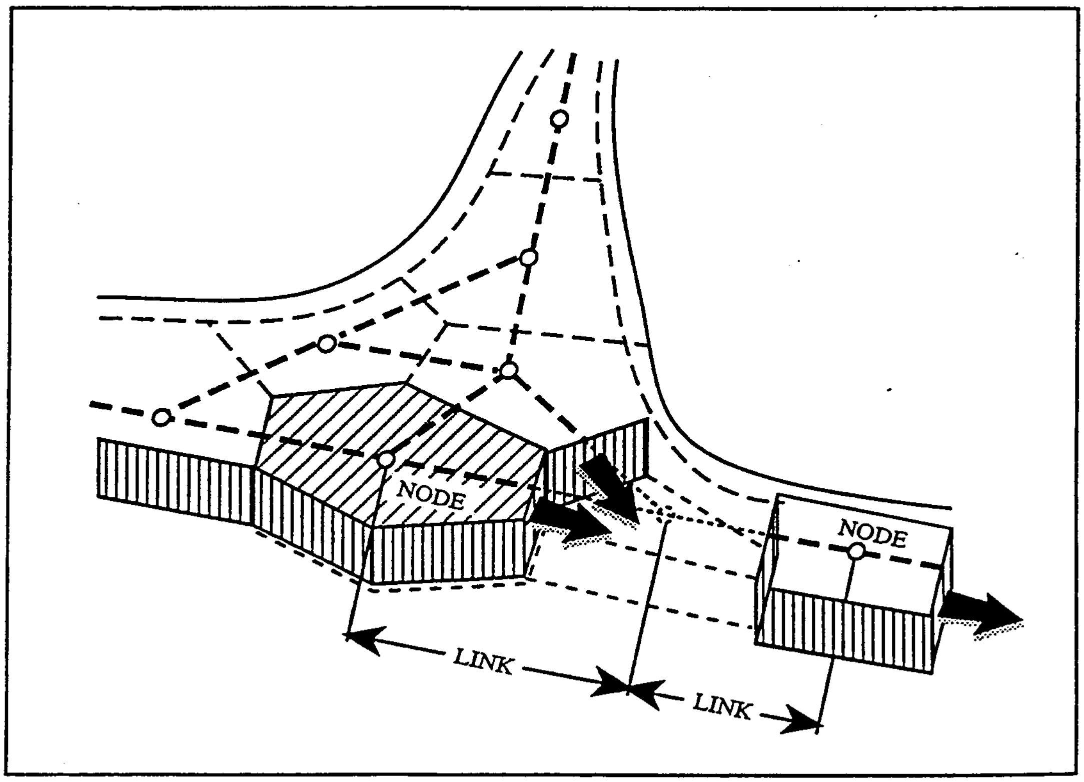

Figure 3. Link-node schematic

The vertical direction is divided into soil layers, which correspond to the layers in the groundwater model. Coupled above the soil layers are the surface water module and the canopy module (Figure 4).

HORIZONTAL GROUNDWATER FLOW MODULE: The groundwater flow module simulates variably saturated horizontal flow in the same soil layers as defined for the vertical processes module. Processes include variably saturated horizontal groundwater flow, fixed-head boundary conditions, and wells.

The subsurface region is divided into a number of layers sufficient to describe vertical variations in soil properties, or to provide suitable resolution of vertical processes. In each vertical layer, the horizontal discretization of the soil is the same as used in the surface water module (Figure 5). Horizontal groundwater flow, both in the unsaturated and saturated zones, is based on Darcy's Law along links, and conservation of volume is enforced for groundwater heads and soil moisture at nodes.

MODEL LINKAGE AND STABILITY CONDITIONS: The surface water module is linked to the vertical processes module through the surface water volume at each node. The vertical processes module is linked to the horizontal groundwater flow module through soil moisture content at each node in each soil layer. The surface water module has no direct linkage to the horizontal groundwater flow module.

The model is governed by two main stability conditions. The channel flow routine of the surface water module uses an explicit link-node scheme that is governed by a one-dimensional Courant condition. Flows in the vertical processes module and the horizontal groundwater flow modules are also treated explicitly. The flows are governed by one-dimensional diffusion conditions in each link, where the diffusion term is the hydraulic conductivity divided by the specific storativity.

CONCLUSION: WDWBM has been designed to simulate long-term wetland processes, but it has all the elements necessary for a comprehensive dynamic watershed simulation model, as well. It was designed to simulate processes in various types of wetlands including riverine, tidal, and depressional. WDWBM, the PC tutorial, and the postprocessing program are available through the WES Engineering Computer Programs Library (ATTN: CEWES-ID-E), phone (601) 634-2581. The reference number for WDWBM is 722-PD-R0008.

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Hales, L. Z., Bird, S. L., Ebersole, B. A., and Walton, R. (1990). "Bolsa Bay, California, proposed ocean entrance system study; Report 3, Tidal circulation and transport simulation and water quality assessment," Miscellaneous Paper CERC-89-17, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Schroeder, P. R., McEnroe, B. M., Peyton, R. L., and Sjostron, J. W. (1988). "The Hydrologic Evaluation of Landfill Performance (HELP) model." Prepared for Office of Solid Waste and Emergency Response, Environmental Protection Agency, Washington, DC, by the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Walton, R., Martin, T. H., Chapman, R. S., and Davis, J. E. (1995). "Investigation of wetlands hydraulic and hydrologic processes, model development and application," Technical Report WRP-CP-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

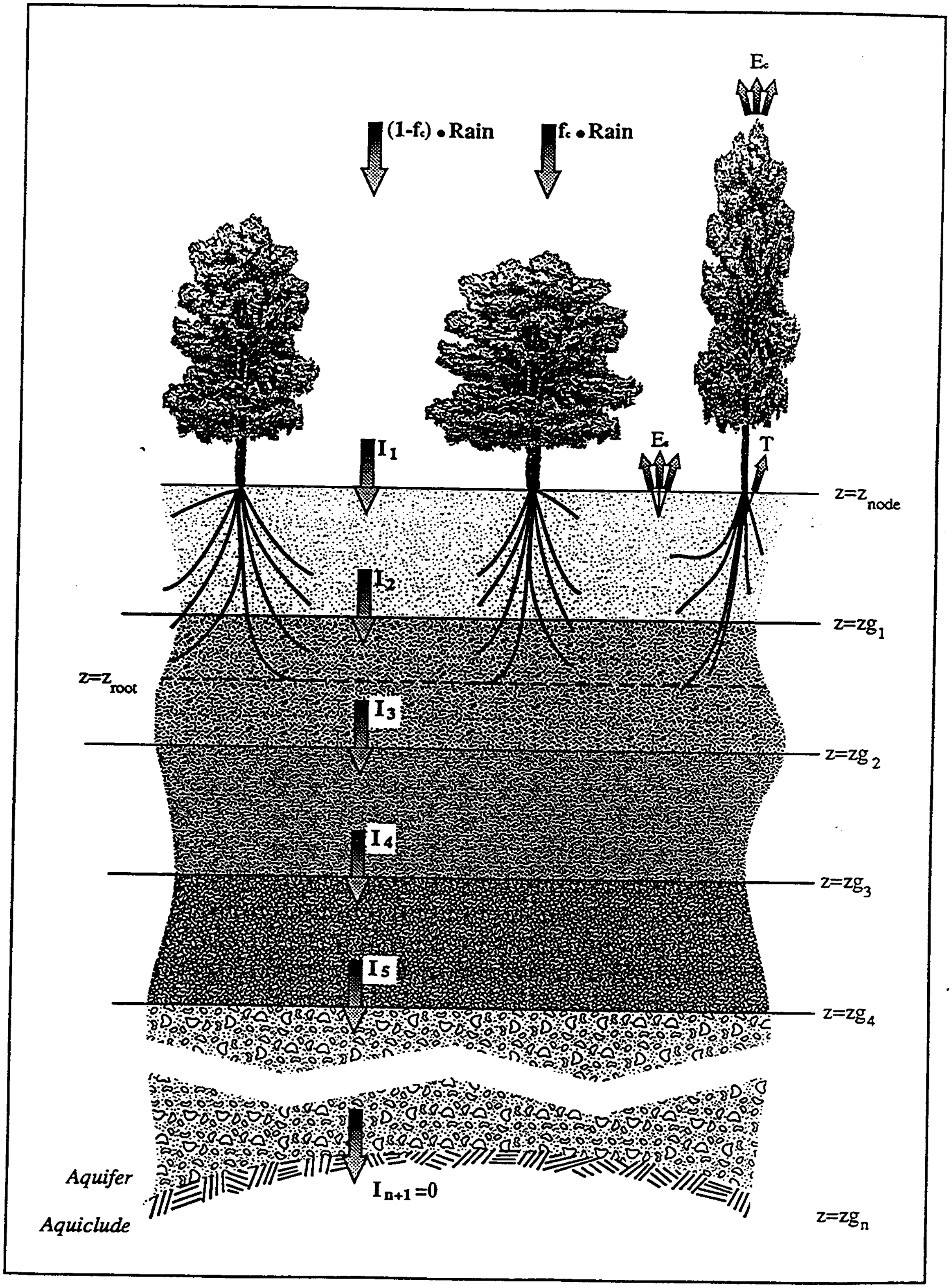

Figure 4. Vertical flow processes

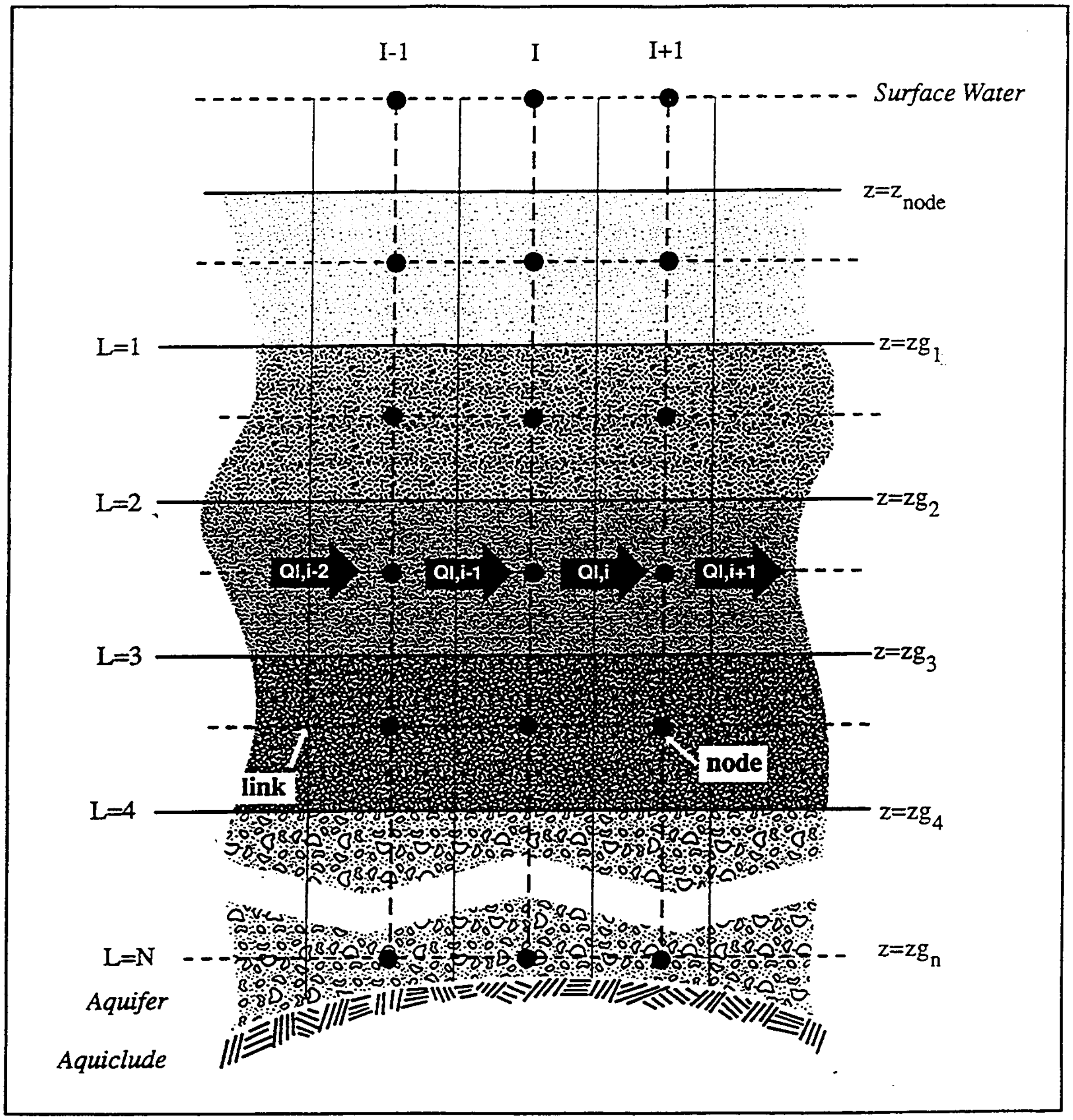

Figure 5. Horizontal groundwater flow

Wright, J. R., and Skiles, J. W. (1987). "SPUR, simulation of production and utilization of rangelands; Documentation and users guide," U.S. Department of Agriculture, Agricultural Research Service, Beltsville, MD.

POINTS OF CONTACT FOR ADDITIONAL INFORMATION: Mr. Jack Davis, U.S. Army Engineer Waterways Experiment Station, ATTN: CEWES-CD-SE, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, phone: (601) 634-3006, author.

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WRP Technical Note HY-CP-5.3
March 1997

Program for Comparison of Wave Theories for Waves Over Cohesive Sediments

PURPOSE: The need to protect, restore, and create wetlands in places such as coastal Louisiana has forced wetland scientists to reevaluate the standard models used for predicting waves, currents, shear forces, and soil behavior based on adaptability to the shallow, complexly connected and muddy marshes, ponds, waterways, and embayments. A program to compare various theoretical models for predicting surface wave propagation over cohesive bottom sediments is presented here. The program provides a tool for coastal scientists and engineers to better understand the interaction of waves and muddy bottom sediments.

BACKGROUND: Wetland scientists and engineers at Louisiana State University are developing new ways of measuring and parameterizing hydrodynamic processes that lead to marsh loss and conversion of land to open water or, conversely, to wetland building and enhancement through increased sedimentation or reduced wave/current forces. The work is a response to the need to understand not only the naturally occurring processes but also the various effects of proposed coastal wetland restoration measures. Coastal researchers need theoretical models that can predict waves, currents, and rheological forces in and on the marsh, and that can be tested using instrument arrays designed for wetland environments. An interactive computerized wave theory guide is discussed below.

WAVE THEORIES: An interactive program was developed that calculates and compares wave characteristics computed from wave theories for propagation over seabeds assumed to be rigid, elastic, viscous, or visco-elastic. The rigid bottom theories include linear wave theory and Stoke's second-order wave theory.

The elastic bottom wave theory is based on Mallard and Dalrymple (1977). These researchers presented a linear analytic solution for periodic water waves passing over a deformable bottom. The solution assumes a constant water depth underlain by a perfectly elastic soil of infinite depth with a shear modulus that represents a soft marine sediment. Soil stresses, displacements, and related water wave kinematics are obtained.

The viscous bottom wave theory is based on Dalrymple and Liu (1978), who presented theories developed for a linear water wave propagating over a two-layer viscous fluid system. The height of the surface wave is specified, and the forced interfacial wave characteristics and wave attenuation rate are determined. A complete model is presented for an upper layer of any depth and a lower layer that can be both deep and shallow. A simplified model is also presented which gives explicit solutions for wave damping when the thickness of the lower layer is greater than the boundary layer thickness developed by the fluid motion.

The visco-elastic wave theory is based on MacPherson (1980). He presented an analysis based on small-amplitude wave theory of the coupled interaction between the bed (which responds in both an elastic and viscous manner) and an overlying layer of inviscid fluid. A dispersion relation is derived from which wave attenuation rates and seabed deflections are calculated.

WBI PROGRAM: The theories mentioned above are included in a program called Wave Bottom Interaction or WBI program (coded in BASIC). Input data for the program are wave height and period, water density, viscosity and depth, and thickness, density, viscosity, and elasticity of the bottom sediments. The program is designed for shallow-water calculations.

Model output is shown in Table 1. The first lines of output echo the input data (Table 2). The next lines give computed values from each of the wave theories for wavelength, celerity, relative water depth, horizontal velocity profile, bottom pressure amplitude, distance for a wave height attenuation of 1/e, wave height amplitude after propagating a distance of 10 wavelengths, bottom wave amplitude, and the phase difference between the surface wave and the bottom wave.

Table 1
Output of the WBI Model

Program WBI
Wave Height (ft) = 20 **Wave Period (s) = 10**
Water Depth (ft) = 100 **Sediment Thickness (ft) = 500**
Sediment Shear Modulus (psf) = 10,000 **Sediment Viscosity (ft2/s) = 1**

	Wave Theory				
Parameter	**Linear**	**Stokes**	**Elastic**	**Viscous**	**Viscoelastic**
Wavelength (ft)	452.1	452.1	435.5	512.0	497.9
Celerity (ft/s)	45.2	45.2	43.6	51.2	49.8
Relative water depth	0.2212	0.2212	0.2296	0.1953	0.2008
Horizontal velocity (ft/s)					
0.0	7.12	7.54	7.39	6.29	6.47
-25.0	5.33	5.54	5.56	4.63	5.02
-50.0	4.18	4.29	4.46	3.41	4.09
-75.0	3.55	3.61	3.95	2.51	3.56
-100.0	3.34	3.39	3.95	1.85	3.39
Bottom pressure amplitude (psf)	290.1	289.3	330.6	2,108.3	618.2
Decay distance (ft, thousand)	0	0	0	4,176.0	21,555.7
Decay/wavelength	0	0	0	0.9923	0.999
Amplitude mud wave (in.)	0	0	13.75	35.00	33.50
Mud wave phase shift (deg)	0	0	180	0	179.99
End of program					

Note: Conversion factors for non-SI to SI units of measurement are as follows: multiply degrees (angle) by 0.01745329 to obtain radians; multiply feet by 0.3048 to obtain meters; multiply inches by 2.54 to obtain centimeters; and multiply pounds (force) per square foot by 47.88026 to obtain pascals.

The program must be run from a BASIC language system such as GWBASIC on IBM-compatible personal computers. Lines 200 to 300 contain the program input data. These data must be modified for each set of desired computations. That is, the values for wave height (H), period (T), etc., must be changed to the values desired. The program will display the output with an option to save it to a file. The program's output is saved to a file called OUT.WBI.

Table 2
Input Data Lines for WBI Program

```
200 REM  INPUT OF WAVE/BOTTOM PARAMETERS
210 REM  THE WATER IS LAYER 1 AND THE HALF SPACE OF SEDIMENTS IS LAYER 2

220 H=20            : REM INPUT "WAVE HEIGHT (FT) =";H
230 T=10            : REM INPUT "WAVE PERIOD (S) =";T
240 D1=100          : REM INPUT "WATER DEPTH (FT) =";D1
250 RHO1=1.92       : REM INPUT "DENSITY OF WATER (SLUGS/CF) =";RHO1
260 MU1=.00001      : REM INPUT "VISCOSITY OF WATER (FT2/S) =";MU1
270 D2=500          : REM INPUT "THICKNESS OF SOFT BOTTOM SEDIMENTS (FT) =";D2
280 RHO2=3          : REM INPUT "DENSITY OF BOTTOM SEDIMENTS (SLUGS/CF) =";RHO2
290 G2=10000        : REM INPUT "SHEAR MODULUS OF BOTTOM SEDIMENTS (PSF) =";G2
300 MU2=1           : REM INPUT "VISCOSITY OF BOTTOM SEDIMENTS (FT2/S) =";MU2
```

REFERENCES:

Mallard, W. W., and Dalrymple, R. A. (1977). "Water waves propagating over a deformable bottom," *Proceedings, 9th Annual Offshore Technology Conference,* OTC 2895. Offshore Technology Conference Office, Dallas, TX.

Dalrymple, R. A., and Liu, P. L. (1978). "Waves over soft muds: A two-layer fluid model," *Journal of Physical Oceanography* 8, 1121-31.

MacPherson, H. (1980). "The attenuation of water waves over a non-rigid bed," *Journal of Fluid Mechanics* 97(4), 721-742.

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Synthesis of Literature on the Use of Water-Stained Leaves in the Delineation of Wetlands

PURPOSE: This technical note synthesizes the literature reviewed in a bibliography, WRP Technical Note HY-DE-6.1. In particular, it examines factors that could potentially influence the occurrence of water-stained leaves in wetland conditions. It also provides suggestions regarding the use of water-stained leaves as a field indicator in the wetlands delineation process.

Figure 1. Water-stained and unstained oak leaves pinned to a tree trunk

BACKGROUND: The 1987 *Corps of Engineers Wetlands Delineation Manual* and the 1989 *Federal Manual for Identifying and Delineating Jurisdictional Wetlands* described three criteria for delineating wetlands: hydrophytic vegetation, hydric soils, and wetland hydrology. Evidence of all three parameters should be present before an area is considered to be a wetland subject to Federal jurisdiction.

According to the Manuals, in order to meet the wetland hydrology criterion, an area must be saturated to the surface or inundated for at least 5% of the growing season (1987) or one week or more during the growing season (1989) in most years. It is difficult to meet this criterion directly because quantitative data on surface water or groundwater levels are rarely available for specific sites.

In lieu of direct measurements of hydrology, the 1989 Manual suggested eleven field indicators that may be readily observed during a field inspection and can be used as evidence that the wetland hydrology criterion has been met. One of the field indicators that was emphasized in the 1989 Manual was the presence of water-stained leaves on the floor of a forested wetland. These leaves are generally grayish or blackish in appearance. It is believed that the darkening of the leaves is related to submersion.

In August 1991, proposed revisions to the 1989 Manual were published in the *Federal Register*, with a request for comments on the technical validity of the delineation protocol. The presence of water-stained leaves was again emphasized as a indicator of wetland hydrology in the proposed 1991 Manual. Subsequently, Corps Districts were directed to return to the use of the 1987 Manual as a basis for delineations until a new, revised Manual could be developed. Updated guidance regarding the use of the 1987 Manual advised Corps personnel to consider water-stained leaves as a secondary hydrologic indicator.

Although water-stained leaves continue to be used as hydrologic indicators for wetland delineation, little is known about the technical validity of this indicator. Accordingly, a literature review was conducted, which has resulted in a bibliography and synthesis of relevant literature.

APPROACH: The literature review consisted of searching pertinent electronic databases; reviewing pertinent articles and their cited references; reviewing recently published journals on related subjects; and reviewing references obtained from subject matter experts.

The authors found no articles specifically addressing water-stained leaves.

Articles related to wetlands are numerous, however, and investigations of decomposition continue to be relatively common. Articles that were selected for inclusion in a bibliography, published as WRP Technical Note HY-DE-6.1, deal with aspects of decomposition in wetlands, general aquatic decomposition, or potentially relevant aspects of wetland ecology.

ANALYSIS: While it seems plausible, even likely, that wetland conditions will often produce water-stained leaves, there is virtually no published evidence that relates the occurrence of water-stained leaves to any other criterion or field indicator of jurisdictional wetlands. However, a review of the related decomposition literature revealed several factors that may influence the occurrence of water-stained leaves. These factors are discussed below.

- Temperature. The observation that chemical and biological processes are almost universally accelerated with increasing temperature certainly applies to decomposition. If the process that brings about water-stained leaves is a component of decomposition, water-stained leaves might be expected to be formed faster, all else being equal, in warmer seasons and in wetlands at less extreme latitudes. On the other hand, if staining is a time-consuming process that is accelerated at greater temperatures, so is decomposition. Therefore, water-stained leaves might be fragmented and mineralized faster in warmer wetlands and, actually, less abundant and persistent. Thus, temperature may determine the season during which water-stained leaves are found, or the parts of the country in which they are most prevalent.

- Redox. Adequate exposure to an aerobic environment may preclude formation of water-stained leaves, but wetlands are well known for their reducing conditions, which greatly influence chemical and biological aspects of decomposition. It has been our personal observation that deciduous leaves kept loosely in aerated water show little color change over time, while similar leaves packed tightly together undergo a rapid (i.e., over a few days) change to a more blue-gray color. The effect of packing is often distinct enough that the centers of adjacent leaves will be discolored while exposed edges will have normal color. If reducing conditions are conducive to formation of water-stained leaves, then water-stained leaves should be observed in wetlands--and many other habitats--where large concentrations of organic matter (and/or inorganic reductants) deplete oxidants in a microenvironment with limited exposure to atmospheric or dissolved oxygen.

- Water. Obviously, moisture is the critical constituent of any wetland. The occurrence of water-stained leaves is probably affected by how much water is present, its periodicity (i.e., wet-dry cycling), the duration of wet periods, the seasonality of wet periods (with respect to temperature, leaf condition, animal activity, etc.), and whether there is sufficient current to transport oxygen and other chemicals or even to move and perhaps abrade the leaves.

  Moist conditions are nearly always more conducive to leaf transformations than dryness. Some studies have found that plant tissue decays faster in alternating wet-dry conditions than in either continuously dry or saturated environments. Moisture provides a solvent for minerals and a medium for surface reactions such as adsorption. Moisture promotes microbial proliferation and enzymatic activity. At the same time, water drastically slows the diffusion rate of oxygen to sites of biological or chemical demand, thus leading to establishment of reducing conditions.

Sites with different amounts of water, different hydroperiods, or different flows will show highly varying rates of leaf transformation. Leaves that fall to a dry forest floor may simply be washed away or buried during the next inundation, while the same leaves falling into wetter conditions may be exposed to very different treatment, leading to discoloration.

- pH. Virtually all studies of effects of pH show that increasing acidity dramatically retards microbial decomposition of plant tissue below a threshold of about pH 5. Wetlands subject to anthropogenic acidification may show unusual effects, but most wetlands probably have pH values conducive to microbial decay. However, the effect of pH on physicochemical transformations such as adsorption of coloring materials to leaf surfaces is apparently unstudied in wetlands.

- Nutrients. Nutrients in sediments and overlying water have been shown by many investigators to influence transformation of detrital leaves. While the nutrient content of wetland soils and overlying waters has been reported often, no relationship has been established between wetland soil or water nutrient content and the coloration of the leaf litter. A likely hypothesis is that leaf discoloration results from precipitation of metal sulfides on leaf surfaces as a result of the same conditions that cause color changes in wet, anoxic soils. It is uncertain what elements are involved and in what concentrations they would need to be present to produce water-stained leaves.

- Sediments. At least part of the color of water-stained leaves may result from a coating of fine soil particles that settles onto the leaves. Particles that are associated with leaf surfaces may compete for adsorption of minerals or, conversely, serve as nuclei to raise concentrations of potentially coloring reactants. Soil particles could also protect the leaves from microbial processes, perhaps by causing complexation of exoenzymes. Severe flooding may bring enough sediments to bury fallen leaves, which quickly promotes anoxia around the leaves. Burial may result in leaves with a different color than those of unburied water-stained leaves. Additionally, rapid sedimentation may result in leaves buried to the extent that water-staining is not apparent.

- Light. Light has been shown to inhibit microbial degradation of plants in water by stimulating growth of photosynthetic microflora. Light may also affect the appearance of detrital leaves either by enhancing color photochemically or, more likely, by destroying color formed in nonphotoreactions.

- Microorganisms and animals. In most benthic communities, the predominant reason for disappearance of detrital leaves is activity of microbes. Fungi, especially aquatic hyphomycetes, are particularly effective in aerobic habitats. Where there are large populations of detritivorous immature insects, animals accelerate mineralization by fragmenting leaves and, in some insects, exposing them to effective gut microflora. Microbial activity may induce discoloration, or perhaps the microbial slime that typically forms during initial decay inhibits discoloration. Water-staining of leaves may also affect microbial and benthic communities by influencing normal succession of decomposing microorganisms, or by making the leaf a less preferred food source.

- Plant species. Leaves of different species respond very differently to decay processes. Leaves have been classified by species with regard to their rates of disappearance in a variety of experiments. Factors that influence decay rates are leaf size and shape, content of nutrients (especially nitrogen), structural compounds such as cellulose and lignin, and presence of metabolic inhibitors, largely polyphenolic "tannins." Clearly these characteristics will likely influence leaf discoloration as well. For example, high concentrations of protein in some leaves may offer more sulfur to react with metals to form a dark surficial precipitate. If leaves are not equally susceptible to discoloration, application of this field indicator is probably dependent upon the species composition of the area in question.

- Leaf condition. Even leaves of the same species undergo varying rates of decomposition depending upon their initial condition with respect to senescence, dryness, and exposure to heat and rain. Presenescent leaves removed by unusual winds are far more nutrient-rich and leach materials faster than do leaves that have been shed by natural abscission. Leaves that remain on the tree after senescence and are exposed for relatively long times, e.g., beech (*Fagus* spp.) and many oaks (*Quercus* spp.), are often sun-bleached and preleached. Heating and drying can cause irreversible complexation reactions between nitrogenous and structural components of leaves but usually accelerate losses by leaching. Drying of fresh tissue makes it leach dissolved materials faster but retards its overall rate of mineralization. It is reasonable to expect that such initial conditions might influence the sensitivity of leaves to staining if leaf color is more than a mere abiotic coating.

CONCLUSION: From an examination of the decomposition literature and wetland ecology literature, it is evident that many variables in wetlands can influence the formation of water-stained leaves. These variables should be considered, in a general sense, when decisions about water-stained leaves are made in the field.

Although there is little technical evidence that directly relates the presence of water-stained leaves with jurisdictional wetland criteria, the frequent occurrence of these darkened leaves in wetlands and the obvious association of water-stained leaves with inundation makes them an indicator worthy of further consideration.

Until more research on the subject yields other pertinent results, it is suggested that water-stained leaves continue to be considered in the delineation process as a secondary hydrological indicator. However, field personnel should be aware that, like drift lines and water marks on trees, the presence of water-stained leaves does not necessarily indicate that inundation of the area occurred for a sufficiently long period of time or during the right time of the year to positively conclude that the hydrologic criterion for jurisdictional wetlands has been met.

REFERENCE:

USAEWES. Jan 93. "Literature Review on the Use of Water-Stained Leaves in the Delineation of Wetlands," Wetlands Research Program Technical Note HY-DE-6.1, Wetlands Research and Technology Center, Vicksburg, MS.

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WRP Technical Note HY-DE-4.1
January 1998

Methods to Determine the Hydrology of Potential Wetland Sites

PURPOSE: This technical note describes a number of field-tested methodologies for evaluating the hydrology of potential wetland sites.

BACKGROUND: The U.S. Army Corps of Engineers "Wetlands Delineation Manual" (Environmental Laboratory 1987) requires that the hydrology, soils, and vegetation of a site be assessed independently for wetland determinations. The presence of hydric soils and hydrophytic vegetation is determined by direct observation. However, the hydrology generally is not determined by field observations alone, since this evaluation involves an extended period of continuous monitoring of inundation or saturation during the growing season. Wetland determinations in routine cases are based in part on ***indicators*** of hydrology that are observable during a brief site visit. Direct hydrologic measurements are possible only in difficult or controversial cases, because field personnel seldom have the time and resources to monitor sites for extended periods of time. Therefore, for routine wetland determinations, the frequency and duration of inundation or saturation are most effectively determined using analytical techniques. Until recently, no analytical methods to determine wetland hydrology had been developed, compiled, and described.

To meet this need, the U.S. Army Corps of Engineers and the Natural Resources Conservation Service (NRCS), in conjunction with other Federal agencies, developed a handbook, "Hydrology Tools for Wetland Determination" (Woodward 1997), which describes a series of analytic approaches to determining the long-term hydrology of a site. The Handbook has undergone extensive peer review to ensure that it serves the needs of Federal and state agencies involved in wetland determination, restoration, and mitigation monitoring. In addition, the tools presented in the Handbook have been field tested to evaluate their strengths and limitations in assessing the hydrology of potential wetland sites (Woodward and Warne 1997).

This technical note summarizes the hydrology tools described in detail in the Handbook (Woodward 1997). An interagency course ("Hydrology Tools for Wetland Determination") is available to Corps personnel, and the course materials are presented in Woodward and others (1996). Further information can be obtained from the individuals listed at the conclusion of this technical note.

DESCRIPTION OF HYDROLOGY TOOLS:

- Stream gauge analysis. In many cases, the timing, frequency, and duration of inundation of riverine wetlands can be evaluated using stream gauge data. This method identifies the critical consecutive-day period (i.e., 5 to 12 percent of the growing season) for which stage is the highest during the growing season, and compares these stage levels with the stage level that would inundate the site. The critical consecutive-day period of highest stage is determined for each of at least 10 years and compared with the minimum stage necessary to inundate the potential wetland site. If the site is continuously inundated for the length of time specified by regulation for at least 5 out of 10 years (that is, at least 50 percent of the years), then stream gauge analysis indicates that the site has wetland hydrology.

If the site has significant topographic relief, the task would be to identify the elevation below which hydrology criteria are met. This may require a detailed site survey. Even though stream gauge analysis alone may not indicate continuous inundation of the area being evaluated for the critical number of days during the growing season for the majority of years, this analysis provides essential information regarding the water budget of the evaluation site.

For example, if analysis reveals that the site is frequently inundated during the growing season, and the site is located in a depressional area underlain by relatively impervious soils, the site might meet wetland hydrology conditions by a combination of inundation and soil saturation. On the other hand, a site that is not commonly inundated for the critical number of consecutive days during the growing season, is not in a depressional portion of the floodplain, and has a substrate composed of pervious material that typically shows scour and flow structures probably does not have wetland hydrology.

This method requires that a stream gauge be located relatively close (300 m) to the area to be evaluated; otherwise, stream profiles must be generated. The stream gauge data must be continuous during the growing season for a minimum of 10 years. If only published streamflow data are available, a rating curve will be necessary to convert streamflows to stages.

More information on stream gauging data is available from the U.S. Geological Survey (USGS) Earth Science Information Center at (800) 872-6277, State USGS Water Resource Service offices, or on the Internet at *http://www.usgs.gov/network/science/earth/usgs.html*. Other data sources are described in Woodward (1997).

- Remote sensing. This procedure correlates precipitation or runoff data with what is seen on aerial photography, commonly U.S. Department of Agriculture (USDA) crop history slides. Using this tool, the analyst determines the number of times that wet signatures are visible at a site on a series of aerial photographs taken over a number of years. Wet signatures include standing water, soil saturation, and stressed crops.

  Photographs may be normal color or color infrared. The USDA Consolidated Farm Service Agency Aerial Photography Lab, (801) 975-3503, can provide aerial photographs over a period of years for cropped areas in many parts of the country. The USGS Earth Resources Observation System data center, (605) 594-6151, is also a major source of aerial photography. Other data sources are described in Woodward (1997).

  Essential to this procedure is to determine whether each photograph was taken during a normal, wetter then normal, or drier than normal growing season, and whether the 3 months prior to the time each photograph was taken were wet, normal, or dry. Because antecedent moisture conditions are so important, it is essential that the date of each aerial photograph be known. WETS tables, developed by the NRCS, provide climate data for the last 30 years at National Weather Service weather stations throughout the country in a convenient format for hydrologic analysis of wetlands. As shown in the sample WETS table (Table 1), other relevant information is provided, such as timing and duration of growing season.

  To use the WETS tables, one compares the actual precipitation for a particular month or year with the "normal" range shown in the table. The Internet address to obtain WETS tables is *http://www.wcc.nrcs.usda.gov/water/w_clim.html*.

Table 1
WETS Table Example[1]

WETS Station: DE SMET, SD2302
Latitude: 4423 Longitude: 09733 Elevation: 01750
State FIPS/County (FIPS): 46077 County Name: Kingsburg
Start yr. - 1961 End yr. - 1990
Temperature: 30 years available out of 30 requested in this analysis
Precipitation: 30 years available out of 30 requested in this analysis

	Temperature (Degrees F)			Precipitation (in.)				
					30 Percent Chance Will Have			
Month	Average Daily Maximum	Average Daily Minimum	Average	Average	Less Than	More Than	Average No. Days with 0.1 or More	Average Total Snowfall
January	23.0	2.4	12.7	0.60	0.31	0.78	2	6.6
February	29.3	9.0	19.2	0.68	0.41	0.89	2	7.0
March	41.3	21.1	31.2	1.60	0.87	1.95	3	8.9
April	58.7	34.2	46.5	2.26	1.28	2.75	4	1.6
May	71.1	45.8	58.5	3.05	1.82	3.69	5	0.0
June	80.3	55.8	68.0	4.02	2.59	4.84	6	0.0
July	86.2	61.1	73.7	3.25	1.96	3.93	4	0.0
August	83.9	58.6	71.3	2.44	1.51	2.95	4	0.0
Septembe r	73.7	48.7	61.2	2.14	1.03	2.61	4	0.0
October	61.0	36.8	48.9	1.78	0.83	2.25	3	0.8
November	41.7	22.5	32.1	0.92	0.34	1.11	2	5.4
December	26.7	8.1	17.4	0.58	0.32	0.73	1	6.0
Annual	--	--	--	--	19.83	26.03	--	--
Average	56.4	33.7	45.1	--	--	--	--	--
Total	--	--	--	23.30	--	--	40	36.3

Growing Season Dates
Requested years of data: 30 Available years of data: 30
Years with missing data 24 deg = 0, 28 deg = 0, 32 deg = 0
Years with no occurrence 24 deg = 0, 28 deg = 0, 32 deg = 0
Data years used 24 deg = 30, 28 deg = 30, 32 deg = 30

	Temperature		
Probability	24 F or Higher	28 F or Higher	32 F or Higher
	Beginning and Ending Dates Growing Season Length		
50 percent*	4/16 to 10/22 189 days	4/27 to 10/9 165 days	5/4 to 9/29 148 days
70 percent*	4/12 to 10/27 198 days	4/22 to 10/13 174 days	5/1 to 10/3 155 days

*** Percent chance of the growing season occurring between the beginning and ending dates.**

[1] **Full WETS tables include a record of monthly total precipitation for each year for the period 1961 to 1995.**

Although NRCS standards for evaluating the hydrology of potential wetland sites using aerial photography vary from State to State, they typically require a minimum of five growing seasons of photography with normal antecedent meteorological conditions. If 5 years of photography taken during normal rainfall seasons is not available, it is common practice to include at least one photograph from a wetter than normal season and one from a slightly drier than normal season.

- Monitoring wells. Areas that are not ponded or flooded for more than a few hours or days, but where the soil remains continuously saturated within the root zone for a significant portion of the growing season, present a special challenge to evaluating the hydrology of potential wetland sites. Observation wells are the most reliable instruments for evaluating the timing, duration, and frequency of saturation at these sites.

  Currently, many groundwater monitoring wells used for wetland regulatory compliance are not properly installed or constructed. Number, locations, and depths of wells are commonly not adequate to determine the long-term shallow groundwater hydrology of a site. Moreover, there continues to be considerable confusion about the design and use of monitoring wells versus piezometers among wetland scientists. Another common problem associated with shallow groundwater analysis is that water-table readings are not frequent enough to determine whether soils remain continuously saturated in the root zone for the critical length of time during the growing season.

  To obtain statistically valid assessment of the long-term hydrology of sites, at least 10 years of water- table data are generally considered necessary. However, few sites have shallow groundwater monitoring well records of this length. Using WETS tables from the nearest climatic station, along with daily precipitation records for the growing season for the time monitoring wells have been installed, may reduce the period of record necessary to evaluate the long-term hydrology of a potential wetland site. Procedures for determining optimal well locations and depths at a site, installing wells, determining the timing and frequency of water-level readings in wells, and reporting results are being further developed at the U.S. Army Engineer Waterways Experiment Station.

- Runoff volumes. Estimates of runoff volume on a daily, monthly, seasonal, and annual basis have been used to determine the frequency and duration of inundation in potholes and floodplain depressions, the antecedent soil moisture conditions for wetlands in semi-arid or arid conditions, and the relationship of drainage and playa surface area.

  Runoff volumes can be determined using the following three procedures:

  — Manual techniques using precipitation and runoff curve numbers.
  — Computer models.
  — Daily runoff volumes from recording stream gauges.

  The curve number procedure is a simple method that provides the investigator with a general understanding of the response of the drainage area to precipitation events and, thereby, provides a clearer picture of the hydrology of potential wetland sites. Data requirements for manual determination of daily runoff using the curve number method include the following: daily precipitation data for a minimum of 30 years from a representative climate station within the area of interest; soils data for the drainage area; land use, cover type, and hydrologic conditions for the drainage area; and planting and harvesting dates for the typical crops in the drainage area.

Data requirements for computer simulation models are generally similar, but vary with the specific program. Standard input data include those listed above, plus watershed characteristics such as drainage area, stream length, and land slope. Most computer models are time consuming to initiate and require trained personnel. However, they can produce accurate runoff simulations that may be required for controversial cases.

- Scope and effect equations. Several equations that were originally developed to evaluate the effect of artificial drainage systems on agricultural soils can help determine the effect of water management measures such as ditches, tiles, and diversions on potential wetland sites. Standard NRCS drainage equations that are currently being used to evaluate the hydrology of sites for wetland regulatory compliance include the ellipse, Hooghoudt, van Schilfgaarde, and Kirkham equations.

  The ellipse equation has long been used to design agricultural drainage and water supply systems in the United States. It is a steady-state equation in that it assumes the system steadily removes rain that falls at a constant rate. The Hooghoudt and van Schilfgaarde are more complex versions of the ellipse equations and accommodate such factors as complex soil stratigraphy and nonsteady-state rainfall. The Kirkham equation takes into account ponded water at a site.

- DRAINMOD. This computer model was originally developed to investigate drainage and subirrigation systems and their effects on water use and crop response (Workman and others 1994). DRAINMOD has subsequently been modified to determine the hydrology of potential wetland sites by incorporating a counting procedure that keeps track of the number of days an area is wet and the number of occurrences of prolonged saturated soil conditions during the growing season.

  Successful use of DRAINMOD requires trained personnel to run the program and the following data:

  — Hourly precipitation.
  — Daily maximum and minimum temperatures.
  — Drainage parameters, such as depth of drains, drain spacing, effective radius of the drains, distance from drain to restrictive layer, drainage coefficient, storage in local depressions, and maximum surface storage.
  — Soil parameters, such as lateral saturated hydraulic conductivity, soil water characteristics by soil layers, volume of water free to drain by soil layers, upward flux, Green and Ampt parameters, and water content at permanent wilting point.
  — Growing season information, such as threshold water-table depth, required duration of high water, and beginning and ending dates for the growing season.

  DRAINMOD has been proven useful in several litigation cases and in other instances where the hydrology of a site was disputed.

APPLICATION: Systematic field testing of these hydrology tools has shown that they generally agree with hydrologic assessments made using proxy hydrologic indicators and long-term observations of the hydrology of sites (Woodward and Warne 1997). The tools have proved successful in a variety of landscape settings in different regions of the United States. When used properly, these procedures can provide valuable information regarding the long-term hydrology of potential wetland sites. These tools are most effective if used in conjunction with the WETS tables and if two or more tools are applied at a given site.

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WRP Technical Note HY-DE-6.1
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Literature Review on the Use of Water-Stained Leaves in the Delineation of Wetlands

PURPOSE: The initial purpose of this review was to determine whether the scientific literature contains a technical basis for the use of water-stained leaves as a field indicator of wetland hydrology. When it was established that no technical information was available on the specific topic of water-stained leaves, the review was broadened to examine factors that could potentially influence the occurrence of water-stained leaves in wetland conditions. A table summarizing the habitat type, location, processes investigated, and environmental factors considered in each of the reviewed articles is presented. A synthesis of this literature, along with suggestions for the use of water-stained leaves in wetland identification, can be found in WRP Technical Note HY-DE-2.1.

BACKGROUND: Water-stained leaves were presented as a significant indicator of wetland hydrology in the 1989 Federal wetlands delineation manual, and currently are used as a secondary hydrologic indicator under the 1987 Corps of Engineers manual. In spite of this emphasis, little is known about the technical validity of this indicator. Accordingly, a literature review was conducted, which has resulted in a bibliography and synthesis of related literature.

APPROACH: The literature review consisted of searching pertinent electronic databases; reviewing pertinent articles and their cited references; reviewing recently published journals on related subjects; and reviewing references obtained from subject matter experts.

The authors found no articles specifically addressing water-stained leaves. Articles related to wetlands, however, are numerous, and investigations of decomposition continue to be relatively common. Articles that met any one of the following four criteria, listed in order of decreasing importance, were selected for inclusion in this bibliography:

- Articles dealing with water-stained leaves or comprehensive aspects of decomposition in wetlands.
- Articles dealing more generally with aquatic decomposition.
- Articles dealing with decomposition in wetlands (but not necessarily including marshes or tidal wetlands).
- Articles dealing with potentially relevant aspects of wetland ecology.

Pertinent information from the articles reviewed is summarized in Table 1, with respect to habitat type, location, process investigated, and environmental factors considered. Although no articles focused on (or even mentioned) water-stained leaves in wetlands or in any other habitat, all were relevant to an overall understanding of conditions in which water-stained leaves might or might not be expected to occur in wetlands or other habitats.

Table 1. Annotations to bibliography. (Footnotes appear on the page following the table.)

REF	LOCATION[1]	HABITAT[2]	GENERA[3]	MAIN[4]	PHYS[5]	CHEM[6]	HYDRO[7]	EDAPH[8]	BIOL[9]	SUBST[10]
1		STR	AL	D					M	
2	GERM	STR	AC, QU	D					M Z	C
3	QUEB	PEA	BE, CX, SC, SP, SX	D		L				M
4	FL	MFW	PN, SG	B D V			W			
5	MS EMBAY	BHF		H			V			
6	IL	FRV	AC, QU	H V			W		M Z	S
7	VA	STR	PL	D						C
8		MAN, MFW, MSW	CX, JU, RZ, ST	B D S		A R				M
9	GA	MFW, SWA	CX, ST	D	T		E			M S
10	GA	SWA		D		P				S
11	LAB	TER		D				M	M	
12	LAB	MIC	PH	D	L					
13	NC	LEV, RIV, SWA	NS	D			W			
14				B D H S V	A S	N	W			
15	NETH	STR	NM	D	S			D		P
16				B D H S V			V W			
17	VA	STR	BE, CO, JU, QU	D		P			M	S
18	MI	PEA	BE, CD, CX, SX	D		A				P S
19	FRAN	STR, FOR, FRV	SX	DH	C T S	A	D			
20	LAB	STR	PI, PP	D	C	L				
21	WALE	TER	AE, FA	B S		P				
22	ENGL	STR	VARIOUS	D						A M P S
23	NC, VA	SWA	AC, CC, NS, QU, TX	D						C M S
24	LAB	SWA	AC	D H		L	V W			
25	LAB	SWA	TX	B D H		A L N P R	W			P
26	VA	SWA	AC, CC, LQ, NS, QU, TX	B D H S V		A	D V			M P S
27	LAB	STR	VARIOUS	B		N			M	S
28	AK	LAK	CX	D		N			A M Z	
29	AK	LAK	CX	D	A L T		D		M	
30	LAB		PP	D						C
31	PR	FFO	PR	B H S		A L N R	E V	A M		
32	KS	STR	CE, QU	D	C					S
33	LAB	STR	AL, SX	D		L				C M S
34	LAB	LAK	MM, NA, NU, SC	D	T	A L R				S
35	VA	SWA	AC, CC, LQ, NS, QU, TX	H V			W			
36	CO	STR	AL	B D	S	P			M Z	C
37	KS	FRV, GAL, STR		D H	S		V			S

REF	LOCATION[1]	HABITAT[2]	GENERA[3]	MAIN[4]	PHYS[5]	CHEM[6]	HYDRO[7]	EDAPH[8]	BIOL[9]	SUBST[10]
38	ARGE	RIV	EI, PN, PS	D	C		D			S
39	WALE	LAK	FA, IS, PT, SX	D	C				M Z	S
40	OH	FRV	AC, PL, PP, SX	H S V	C					
41	NH	STR		S				S	M	Q
42	TX	FRS	LU, NE, TY	D			W			P S
43	CSTL PLN	BHF	VARIOUS	S V		A R	V	M		
44	VA	FRV		H V						
45	LA	SWA	VARIOUS	B D	S	A N R				
46	ENGL	SUP	AC	D S		P			Z	C
47	LAB			D						M
48	NETH	LAK	NM	D					M Z	
49	GA	STR	AC, TX	D H					Z	S
50	ALBE	PEA	SP	D	T		D W	M		
51	LA	FOR, SWA		H V					M	
52	UT	STR	AC	D	T					
53	AK	LAK	CX	D		P			M	
54	NC, VA	SWA	AC, CC, NS, QU, TX	V			V W			
55	MI	FRV, STR	FR	D					Z	
56		SSU		B S		A N P R		A D M S		
57	GA	MSW, SWA	CX, ST	D						M S
58	TN	STR	AC	D		P			M Z	
59	LAB		FR, PE, ST	B					M	M Q
60	SWED	FEN, STR	CX	D						M
61	SWED	MFW	CX, ME, SC	V		N				M
62		SSU		S		A R		A M S		
63	MI, KS	STR	VARIOUS	D		L			M Z	A C S
64	IL	FFO, FOR	AC, CY, QU	D H			W			C S
65	ASTL	STR	CS, EU, MM, SX	D	C				Z	S
66	SC	PON	VARIOUS	V						M S Q
67		SSU		B S V		A L N P R		A D M S		
68	WI	MFW	SC, SM, TY	D	T	N				P S
69	LA	SSU		B D		N R	V			
70	OH	LAK	AC	D	T	A	D			
71	MI	STR	FR	D		A		S	M	C
72	IA	LAK	PO	D			D		Z	
73	SAFR	LAK	PT	D		N				C
74	NZEA	STR	NO	D S	C S				M Z	
75	LAB	TER		D			V	M		
76	MA	PEA	MC	D			D	M		M

REF	LOCATION[1]	HABITAT[2]	GENERA[3]	MAIN[4]	PHYS[5]	CHEM[6]	HYDRO[7]	EDAPH[8]	BIOL[9]	SUBST[10]
77	ALL US	VARIOUS	VARIOUS	H S V						
78	INDI	MFW, SSU, SUP	TY	B D			V W			P
79	SC	FFO	AC, CY, FR, LR, PL, QU, SX	V			V W			
80	SC	FFO	AC, CY, FR, LR, PL, QU, SX	B D	S	L	V			C M S
81	LAB	TER		D			V	M		
82	LAB	TER		D			V	M	M	
83	TN	PON, STR	QU	D	C L T	P			Z	
84		STR		D	T					M
85	MI	STR	CY, QU	D						M S
86	ALBE	FOR	PI, PP	D		L	V			C S
87	ALBE	FOR	PI, PP	D	T	L				C S
88	LAB	STR	AL	D	C	L				
89	TN	FOR, STR	AC, LR, QU	D	A	L	W			S
90	NSCO	STR	AC, QU	D	T	P				
91	SC	FRV, STR	NS	D	C				Z	C
92	INDI		EI	D		N			M	M
93	NC, VA	SWA	AC, CC, NS, QU, TX	D S				D M		P S
94	NC	STR	CO, QU, RD	D	A C S					
95	TN	FOR, PON, STR	AL, PL, QU	B D	AC	L	W		M	S
96	MO	LAK, FRS	NE, QU	D			W			S
97	NC, VA	SWA	AC, CC, LQ, NS, QU	B D	A		V W			S

[1]Place where research was performed. Two-letter forms are standard abbreviations for US states or commonwealths. "LAB" indicates that observations were made in the laboratory. Four-letter abbreviations represent Canadian provinces or other countries, as follows: ALBE-Alberta; ARGE-Argentina; ASTL-Australia; ENGL-England; FRAN-France; GERM-Germany; INDI-India; NETH-Netherlands; NSCO-Nova Scotia; NZEA-New Zealand; QUEB-Quebec; SAFR-South Africa; SWED-Sweden; WALE-Wales. In rare instances (e.g. 5,43), the most specific or useful notation of location is not a political jurisdiction but a physiographic region (e.g., Mississippi embayment and coastal plain, respectively).

[2]Specific habitat(s) in which this work was done, as named by the investigators: BHF-bottomland hardwood forest; FEN-fen; FFO-floodplain forest; FOR-forest, upland; FRS-floodplain, reservoir; FRV-floodplain, riverine; GAL-gallery forest; LAK-lake; LEV-levee; MAN-mangrove swamp; MIC-microbial communities; MFW-marsh, freshwater; MSW-marsh, saltwater; PEA-peatland; PON-pond; RIV-river; SSU-soil, submerged; STR-stream; SUP-soil, upland; SWA-swamp, freshwater; TER-terrestrial.

[3]AC-Acer; AE-Aesculus; AL-Alnus; BE-Betula; CC-Chamaecyparis; CD-Chamaedaphne; CE-Celtis; CO-Cornus; CS-Casuarina; CX-Carex; CY-Carya; EI-Eichhornia; EU-Eucalyptus; FA-Fagus; FR-Fraxinus; IS-Isoetes; JU-Juncus; LQ-Liquidambar; LR-Liriodendron; LU-Ludwigia; MC-Myrica; ME-Menyanthes; MM-Myriophyllum; NA-Najas; NE-Nelumbo; NM-Nymphoides; NO-Nothofagus; NS-Nyssa; NU-Nuphar; PE-Peltandra; PH-Phragmites; PI-Pinus; PL-Platanus; PN-Panicum; PO-Polygonum; PP-Populus; PR-Prestoea; PS-Paspalum; PT-Potamogeton; QU-Quercus; RD-Rhododendron; RZ-Rhizophora; SC-Scirpus; SG-Sagittaria; SM-Sparganium; SP-Sphagnum; ST-Spartina; SX-Salix; TX-Taxodium; TY-Typha.

[4]Main subjects considered by the article: B-biogeochemistry:nutrient cycling, uptake, release; D-decomposition: loss (or accumulation) of matter and individual constituents over time; H-hydrology; S-sediments and soils; V-vegetation: abundance, distribution, diversity, primary productivity.

[5]Physical factors that may influence the occurrence of water-stained leaves: A-abrasion, scouring, mechanical fragmentation; C-current, turbulence; L-light; T-temperature; S-sedimentation, siltation, burying.

[6]Chemical factors that will affect leaf appearance: A-anoxia, dissolved oxygen concentration; L-leaching from substrate; N-nutrient availability in surrounding water and soil; P-pH, acidity, anthropogenic acidification; R-redox, extent of chemical reducing conditions.

[7]Hydrological effects, especially on the presence of leaves: D-depth of water; E-export of substrate; G-groundwater; V-variability of conditions, including periodicity and seasonality, duration, frequency; W-wet, i.e., overall effect of flooding and submergence.

[8]Edaphic factors that will affect the presence and appearance of leaves: A-aeration of soil; D-depth of soil; M-moisture in soil; S-structure of soil, including composition, texture and density.

[9]Biological factors that may alter the appearance of leaves: A-algae and other primary producers; M-microorganisms, especially bacteria and fungi, other than primary producers; Z-animals.

[10]Substrate features: characteristics of the leaves themselves which will likely influence their presence and discoloration: A-age; C-condition: degree of microbial colonization, extent of leaching, presence of surficial coatings, particle size and shape, compaction in habitat; M-molecular constituents and structure: inorganic nutrients, metabolic inhibitors, structural macromolecules, sclerophylly; P-parts: differentiation of response by separate parts, e.g. leaves, petioles, stems, rhizomes; S-species-specific effects; Q-quality, with respect to lability and refractivity to degradation, suitability as a microbial substrate or animal food.

Citations are listed alphabetically by authors' names. Citation numbers key the bibliographic information to the annotations in Table 1.

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CONCLUSIONS: Although there is little technical evidence that directly relates the presence of water-stained leaves with jurisdictional wetland criteria, the frequent occurrence of these darkened leaves in wetlands and the obvious association of water-stained leaves with inundation make them an indicator worthy of further consideration. To improve the utility of water-stained leaves in the wetland delineation process, it is recommended that research be conducted to address the following preliminary questions: (1) What is the origin and composition of the color of water-stained leaves, (2) What environmental factors typically result in discoloration of leaves (e.g., moisture, redox, temperature, microbial activity) and how long does it take for leaves to become stained, (3) Are all species of leaves equally susceptible to discoloration, and (4) Is the staining process reversible?

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Wetland Surface Water Processes

PURPOSE: This technical note summarizes hydrologic and hydraulic (H&H) processes and the related terminology that will likely be encountered during an evaluation of the effect of surface water processes on wetland function. The technical note provides general guidance to personnel in the field who lack specific expertise in H&H processes but are still faced with the regulatory responsibility of wetland permit evaluation. Future technical notes will provide detailed information on data sources and methods of analyses associated with individual H&H processes.

BACKGROUND: The hydrologic and hydraulic characteristics of a wetland influence all wetland functions and, consequently, should be an initial focus of a wetland evaluation. The processes by which water is introduced, temporarily stored, and removed from a wetland are commonly known as the water budget. Water is introduced to a wetland through direct precipitation, overland flow (or runoff), channel and overbank flow, groundwater discharge, and tidal flow. Temporary storage includes channel, overbank, basin, and groundwater storage. Water is removed from the wetland through evaporation, plant transpiration, channel, overland and tidal flow, and groundwater recharge.

The relative importance of the above processes varies with wetland type (i.e. riverine, tidal, depressional), which depends on regional factors such as climate, geology, and physiography. In particular, the physiography or the topographic and bathymetric variation in and around a wetland affects the residence time within a wetland, which can either increase or reduce the relative impact of the H&H process. For example, the water budget of riverine wetlands with residence times on the order of hours to days is controlled primarily by differences in channel and overbank inflow and outflow. Depressional wetlands, on the other hand, which can have residence times ranging from weeks to seasons, have water budgets that depend for the most part on direct precipitation, evaporation, transpiration, and groundwater interaction. A flow chart illustrating the interaction between wetland H&H processes is provided as Figure 1.

- Wetland Basin Characteristics. The physiography or basin characteristics of a wetland and its surrounding watershed influence both the interaction and relative importance of individual H&H processes. Basic information on geometric features (basin length, width, depth, upstream drainage area), location and physical characteristics of hydraulic structures, and land use is essential to understand the water budget within a wetland. Initial estimates of these physical features can be derived from U.S. Geological Survey (USGS) topographic maps, aerial photography, wetland inventory maps, and National Ocean Service (NOS) charts for tidal areas. Refinements to the initial estimates can be made from data collected during a field visit. Useful spatial relationships that can be derived using these data are stage-area and stage-volume curves, which allow one to quickly estimate the extent of areal flooding given point surface elevation measurements.

- Precipitation. Surface water processes within a wetland are tied to both local and regional precipitation patterns. Precipitation can influence a wetland water budget directly through rain and snowfall within the physical boundaries of the wetland and the associated runoff, or indirectly through inflows from upstream watersheds. Information required to estimate the influence of precipitation ranges from general regional and seasonal variability to the frequency and magnitude of individual storm events. Complete daily records and statistical summaries of regional meteorological conditions are available through the National Weather Service (NWS).

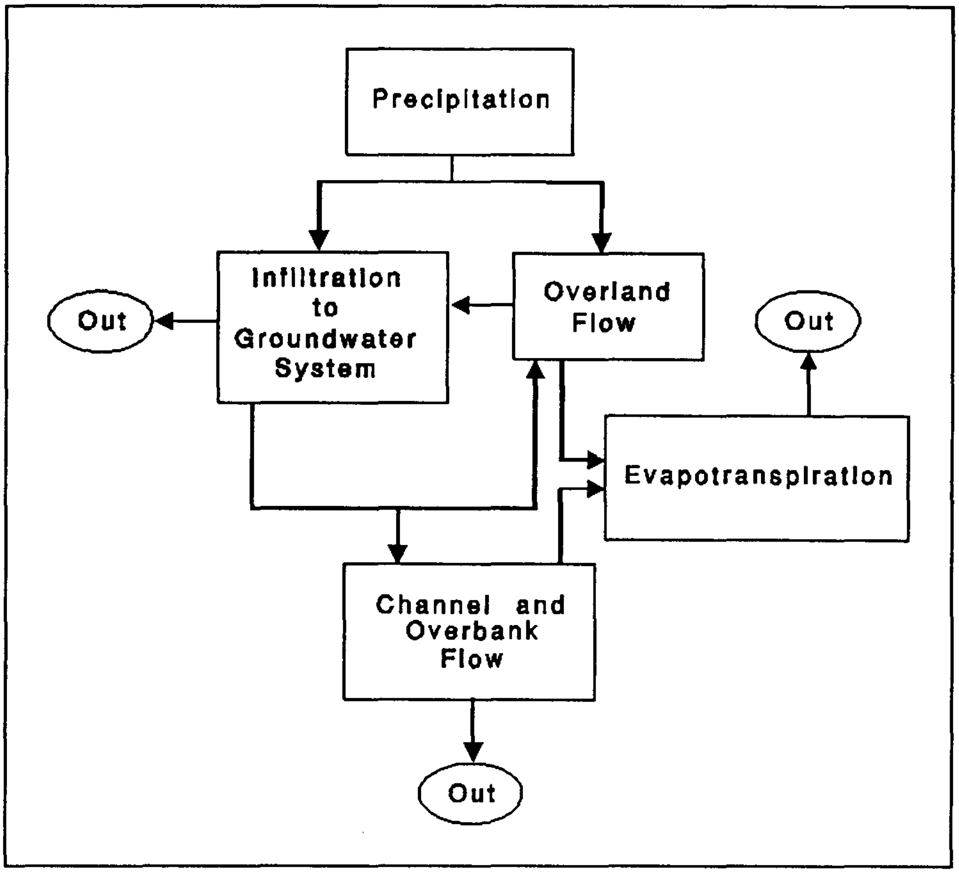

Figure 1. Flowchart of surface water H&H processes

- Evaporation and Transpiration. Evaporation is the process by which water in a liquid or solid state is converted to water vapor and lost to the atmosphere. Surface water loss due to evaporation depends on meteorological conditions, such as air temperature, humidity, and wind speed, and ground conditions such as vegetative cover and soil moisture content. Regional estimates of evaporation rates are obtained by pan, lake, and reservoir evaporation studies and are available through the NWS. Pan evaporation rates are higher than for lakes and reservoirs, so as a rough rule, pan evaporation rates should be reduced by 30% when applied to open water within a wetland (Kohler 1952).

  Transpiration results from root uptake by emergent plants and the subsequent loss through leaf surface area. Estimates of transpiration rates are related to vegetative density, soil moisture content, and depth to the deep root zone. These data are available through state agricultural extensions. Often the effects of evaporation and transpiration on a wetland water balance are combined into a single estimate of water loss called evapotranspiration. A number of empirical methods for estimating evapotranspiration are available in the literature (Christiansen 1968; Kadlec, Williams, and Scheffe 1986).

- Channel and Overbank Flow. Channel and overbank flow is the downgradient response of accumulated surface water to gravity. Channel and overbank flow can significantly impact the introduction, temporary storage, and removal of water within all types of wetlands. Flow rates are closely linked to net precipitation and the resulting processes, such as watershed runoff, ice and snowmelt, and flood flows from upstream watersheds. Discharge estimates can be obtained from USGS stage-discharge relationships derived for gaged rivers. The influence of channel and overbank flow varies seasonally to yearly in magnitude, duration, and frequency. As a consequence, care should be exercised in the use of measured flow rate and stage data to determine the areal extent and duration of flooding within the bounds of a wetland. The USGS publishes mean annual peak flow rates and flood flow events for selected return intervals (Barnes and Golden 1966) that can be used to view limited field data in a proper statistical perspective. In addition, much of the data compiled on river stage, discharge, and reservoir volumes are available through data systems, such as the USGS WATSTORE (National Water Data Storage and Retrieval System), that provide daily observations and statistical summaries.

- Overland Flow. Overland flow occurs when the infiltration capacity of the soil is exceeded. The resulting runoff follows topographic gradients until it either enters a channel or accumulates in a local depression where it ponds, infiltrates, or evaporates. Estimates for overland flow can be obtained from methods such as the Rational Formula (Bedient and Huber 1988), which relates discharge to rainfall intensity, watershed area, losses such as infiltration and detention storage. Data on runoff coefficients for various land coverage types can be obtained from standard reference handbooks (Chow 1964) and the SCS Engineering Field Handbook (1992).

- Groundwater Recharge and Discharge. Differences between surface water elevations and the groundwater table can result in either groundwater recharge or discharge. Recharge occurs when the surface water elevation exceeds the groundwater table, and discharge when the opposite occurs. Given that the surface water elevation within a wetland usually varies more rapidly than the groundwater table, the soils and sediment within a wetland can act as both a source or sink of surface water. Estimates of the volume flow rate of groundwater discharge can be obtained by applying Darcy's Law (Freeze and Cherry 1979). The data required to evaluate this process include surface water elevations, groundwater elevations, and the hydraulic conductivity of the soil or sediment. These data can be obtained from state offices of the USGS and the SCS. Regional groundwater level information is also available through WATSTORE.

- Tidal and Related Flow. The impact of the tides on the water budget of a coastal or estuarine wetland varies temporally and regionally. This is because both tidal periods and amplitudes exhibit a wide variation from one location to another. Tide tables, tidal current tables, and tidal current charts can be obtained from the NOS. Daily information on high and low tides is available in local newspapers. In addition, related flows such as freshwater inflows and wind-driven currents and waves can radically alter periodic volume balance and salinity distribution within a tidal wetland. Estimates of freshwater inflow should include upstream flows gaged at the fall line and runoff from watershed area below the fall line. Methods of estimating variations in water level due to wind forcing is provided in the Shore Protection Manual (USAEWES 1984).

CONCLUSION: This technical note provides a framework for examining surface water processes within a wetland. The information and supporting references presented can be used by field personnel as a guide to identifying the H&H processes that significantly influence wetland function, understanding the interrelationships among the various H&H processes, and identifying the data required to determine the relative importance of individual H&H processes. In general, the overview provided by this technical note should be used to avoid the omission or misinterpretation of specific H&H mechanisms and their role in determining the overall water budget of a wetland.

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Wetland Groundwater Processes

PURPOSE: This technical note summarizes hydrologic and hydraulic (H&H) processes and the related terminology that will likely be encountered during an evaluation of the effect of ground-water processes on wetland function. This technical note provides general guidance to personnel in the field who lack specific expertise in H&H processes but are still faced with the regulatory responsibility of wetland permit evaluation. Future technical notes will complement this overview by presenting more detailed information on data sources and methods of analyses associated with individual H&H processes.

BACKGROUND: The hydrologic and hydraulic characteristics of a wetland influence all wetland functions, and consequently should be an initial focus of an evaluation. The processes by which water is introduced, temporarily stored, and removed from a wetland are commonly known as the water budget. Water is introduced to a wetland through direct precipitation, overland flow (or runoff), channel and overbank flow, groundwater discharge, and tidal flow. Temporary storage includes channel, overbank, basin, and groundwater storage. Water is removed from the wetland through evaporation, plant transpiration, channel, overland and tidal flow, and groundwater recharge.

The relative importance of groundwater processes on the water budget varies with the wetland type (i.e., riverine, tidal, depressional), and regional factors such as climate, hydrogeology, and physiography. Useful reviews of the influence of groundwater processes in wetlands can be found in Carter and Novitzki (1986) and Winter (1988). To evaluate whether groundwater at a site influences wetland functions, it is important to understand individual groundwater processes, the role they can play in various wetland types, and how to evaluate their contributions to the water budget.

FACTORS AFFECTING GROUNDWATER FLOW: Groundwater flow is influenced by a number of factors, including hydraulic gradients, hydraulic conductivity, porosity, and storage coefficients. While these parameters are simple to understand, they are often difficult to quantify. Information on local and regional soil parameters and piezometric heads can usually be obtained through state and Federal Geological Surveys or the Soil Conservation Service (SCS). Data sources include databases such as the U.S. Geological Survey WATSTORE, state wetland inventories, soil surveys, and SCS soil maps.

- Hydraulic Gradients. The hydraulic gradient is the difference in piezometric head between two locations divided by the distance between them. Generally, this is measured by installing several wells, bore holes, or piezometers, and measuring the head in each. For groundwater flows to or from the surface water, the elevation of the surface water is the upper piezometric head.

- Hydraulic Conductivity. This is the ability of the soil to conduct water under hydraulic gradients. The hydraulic conductivity or permeability depends on soil characteristics such as type (i.e. clay or sand), size, shape, and packing. Hydraulic conductivity can be estimated in a number of ways (Driscoll 1986, Lamb and Whitman 1969). It can be roughly estimated, given the soil composition and texture, or calculated based on a soil size analysis. Local values of hydraulic conductivity can be measured by performing a slug test in a piezometer or well location. Field-wide measurements can be determined from an aquifer performance (pump) test, in which one well is pumped and the variation of the piezometric head in nearby wells is observed over time. Values of hydraulic conductivity have been found to range from 10^{-8} meter per second in clay soils to 10^{-2} meter per second in well-sorted gravel formations (SCS 1992).

- Porosity. Porosity is the fraction of a soil volume occupied by voids, and represents the potential area through which water can flow. It is usually measured in the laboratory from a soil sample, although knowledge of the soil type can give a fair estimate of porosity. Together with the flow rate calculated from Darcy's Law (Freeze and Cherry 1979), the soil porosity can be used to estimate groundwater travel times.

- Storage Coefficient. The storage coefficient is a measure of the amount of water stored in an aquifer for a unit rise in the elevation of the piezometric head. For an unconfined aquifer, the storage coefficient (or specific yield) determines the rate of change in elevation of the water table. Values of this parameter can be estimated, crudely, from a knowledge of the soil material. However, the most reliable estimates of formation storage coefficients are usually determined from aquifer performance tests.

H&H PROCESSES. The primary H&H processes that influence wetland groundwater interaction are precipitation, infiltration, groundwater discharge/recharge, shallow and deep groundwater flow, groundwater pumping, and evaporation and transpiration. A schematic showing the relationship between these processes is shown in Figure 1.

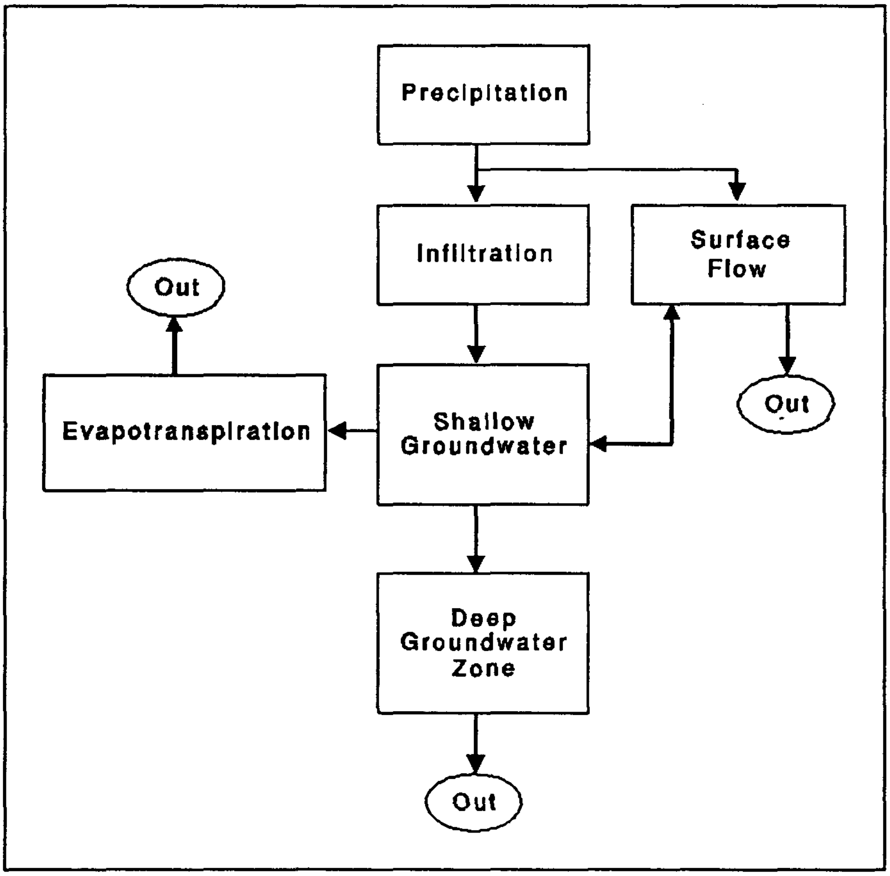

Figure 1. Flowchart of groundwater H&H processes

- Precipitation. Groundwater processes associated with wetlands result from local and regional precipitation patterns. Precipitation can influence a wetland water budget directly through rain and snowfall within the physical boundaries of the wetland, or indirectly through inflows from upstream watersheds. Information required to estimate the influence of precipitation ranges from the regional and seasonal variability to the frequency and magnitude of individual storm events. Complete daily records and statistical summaries of regional meteorological conditions are available through the National Weather Service.

- Infiltration. In areas where the surface water is not in direct hydraulic contact with the groundwater, surface water moves generally vertically downward through the unsaturated zone to the saturated zone (i.e., water table), or a perched water level above an impervious soil layer. The infiltration rate is governed by a number of factors, including the depth of surface water, the initial soil moisture content, and soil properties such as hydraulic conductivity. Infiltration and subsequent groundwater recharge are generally more important for upland and depressional sites, where stream inflows may not be the major factor creating the wetland. Sites with low-permeability soils may result in overland flow to the wetland or stream, whereas high-permeability soils can lead to significant infiltration to the underlying groundwater system. Where significant infiltration exists, a rapid increase in the elevation of the local water table can occur. This situation is most likely near streams or depressional wetlands, where the surrounding water table is near the ground surface and the residual moisture content high. The resulting high gradients from the groundwater system to the stream or wetland can cause significant groundwater discharge. Infiltration rates are estimated by direct measurements such as percolation tests and analytic methods (Chow 1964).

- Groundwater Discharge and Recharge. Groundwater discharge occurs where the elevation of the water table (piezometric surface) exceeds that of the surface water. Groundwater recharge results when the opposite occurs. Estimates of the rate of groundwater discharge or recharge can be obtained by applying Darcy's Law. The data required for this evaluation are synoptic surface water elevations, groundwater elevations or piezometric heads, and the hydraulic conductivity of the soil or sediment. At some sites, for example within the Prairie Pothole region, the deposition of organic material in the permanent pool may significantly reduce the local hydraulic connection to the groundwater system. However, hydraulic conductivities in the adjacent areas may be significantly larger, and become important as the water level in the wetland rises. In addition, wetlands have been observed to change seasonally from discharge to recharge or flow-through systems. As a result, it is important to examine both the spatial and temporal variability of wetland groundwater characteristics.

- Shallow Versus Deep Groundwater Flow. The interaction between the shallow groundwater zone and the underlying regional groundwater system can influence the rate of shallow groundwater transport, and thus the interaction with surface waters and wetlands. In some systems, an aquitard (i.e. confining layer) exists that decouples the shallow and deep groundwater zones. In these cases it is important that local shallow-water well piezometric heads (as opposed to regional groundwater data) are used to assess wetland groundwater function. On the other hand, hydraulically coupled aquifers can exhibit upward or downward flow depending on the relative piezometric heads and spatial variations in soil and sediment properties. The potential influence of the deep groundwater zone can be examined by inspecting available stratigraphic information for evidence of aquitard material or other significant changes in formation composition. This process can be further examined utilizing measurements of head from shallow piezometers and deep wells to develop piezometric contours of the system.

- Groundwater Pumping. Groundwater pumping or pump-recharge can influence groundwater processes in the vicinity of a wetland by altering the piezometric surface, and thus hydraulic gradients. Evidence of pumping can be seen in piezometric contours, or records obtained from agricultural extensions, Geological Surveys, and the Departments of Health or the Environment. In areas where pumping is used for irrigation, pumping is often seasonal, and the effects on shallow groundwater movement can vary. In addition, irrigation supported by deep-water well pumping may increase infiltration to near-surface aquifers.

- Evaporation and Transpiration. Evaporation from the groundwater zone occurs only when the water table is within a few inches of the ground surface. Evaporative losses depend on meteorological conditions such as air temperature, humidity, and wind speed, ground conditions such as vegetative cover, and the soil moisture content.

  Transpiration results from root uptake by emergent plants and the subsequent loss through leaf surfaces. Over extended dry periods, transpiration can cause the water table to decline as far as the deep root zone of the wetland vegetation. Estimates of transpiration rates are related to meteorological conditions, vegetation characteristics, soil moisture content, and the depth to the deep-root zone. These data are available through state agricultural extension offices.

  Often the effects of evaporation and transpiration on a wetland water balance are combined into a single estimate of water loss called evapotranspiration (ET). In depressional wetlands, where there is no significant outlet, and in wetlands where the water table is often close to ground surface, ET may be the most significant factor in removing water from the system. A number of methods for estimating potential or actual evapotranspiration at the ground surface are presented in the literature (Christiansen 1968; Kadlec, Williams, and Scheffe 1986).

CONCLUSION: This technical note provides a framework for examining groundwater processes within a wetland. The information and supporting references presented can be used by field personnel as a guide to (1) identifying the H&H processes that significantly influence wetland function, (2) understanding the interrelationships among the various H&H processes, and (3) identifying the data required to determine the relative importance of individual H&H processes. In general, the overview provided in this technical note should be used to avoid the possible omission or misinterpretation of specific H&H mechanisms and their role in determining the overall water budget of a wetland.

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WRP Technical Note HY-EV-5.1
August 1993

FastTABS Software for Evaluation of Wetlands Hydrodynamics

PURPOSE: This technical note documents how recent software developments (FastTABS) can be used in the evaluation of two-dimensional (2-D) wetland hydrodynamics.

BACKGROUND: Rivers, reservoirs, and estuaries have been modeled for a number of years using the U.S. Army Corps of Engineers TABS numerical modeling system. TABS is a family of numerical models that can simulate hydrodynamic, sediment, and constituent transport processes in these water bodies. One of the most attractive features of the TABS system is the ability to simulate wetting and drying of shallow areas caused by either discharge fluctuations in rivers or tidal fluctuations in estuaries. While this capability has existed for some time, it has only recently been used for applications where wetlands were the primary interest.

Recently,. there has been an increased awareness of the impacts of Corps projects in neighboring wetland areas. It became imperative to determine the impacts of the projects, whether they were deepened navigation channels or hydraulic structures, on wetlands. In some cases, the Corps was asked to mitigate their projects by creating new wetland areas where they didn't previously exist or by renovating deteriorated wetlands. Based on the wetland type and function desired, suitable hydraulic conditions need to be designed into the created or renovated wetland. Given that hydraulic conditions are often not controllable, geometry of the wetland is the single controllable characteristic that can affect frequency and depth of inundation. The design of wetlands then becomes an iterative process that requires several trial geometries for a given set of hydraulic inputs. Since this iterative process can be time consuming, efficient model setup and boundary condition assignment is required.

EXISTING TOOLS: The TABS system consists of many separate programs that individually address different aspects of the modeling process (Thomas and McAnally, 1990). These include mesh development, geometry input file generation, boundary condition definition, hydrodynamic input file generation, job status monitoring, and post-processing of the results. Separate input files are needed for using each of the different flow and transport models within the system. TABS has historically been used in a batch-oriented mainframe computer environment but has recently been converted to personal computers and workstations.

SOFTWARE DEVELOPMENTS: A new graphical implementation of TABS (FastTABS) (Lin, et al, 1991) has been developed that successfully addresses the need for efficient model setup, execution, and analysis. It is mouse driven with pull down menus (Figure 1) and requires a minimum of manual data entry to complete an application from start to finish. FastTABS was designed to allow easy application of each of the models in the TABS system which include hydrodynamics, constituent and sediment transport. In this technical note, only hydrodynamic capabilities are addressed. Developments in constituent and sediment transport will be presented in future technical notes.

DEMONSTRATION SITE APPLICATIONS: Several demonstration sites in the WRP have been modeled using the TABS system with good results. Two of these include: Bodkin Island (a black duck habitat that was to be created from dredged material in Chesapeake Bay) and the Galilee Bird Sanctuary (a reclaimed brackish marsh in Rhode Island). The modeling of each site provides examples

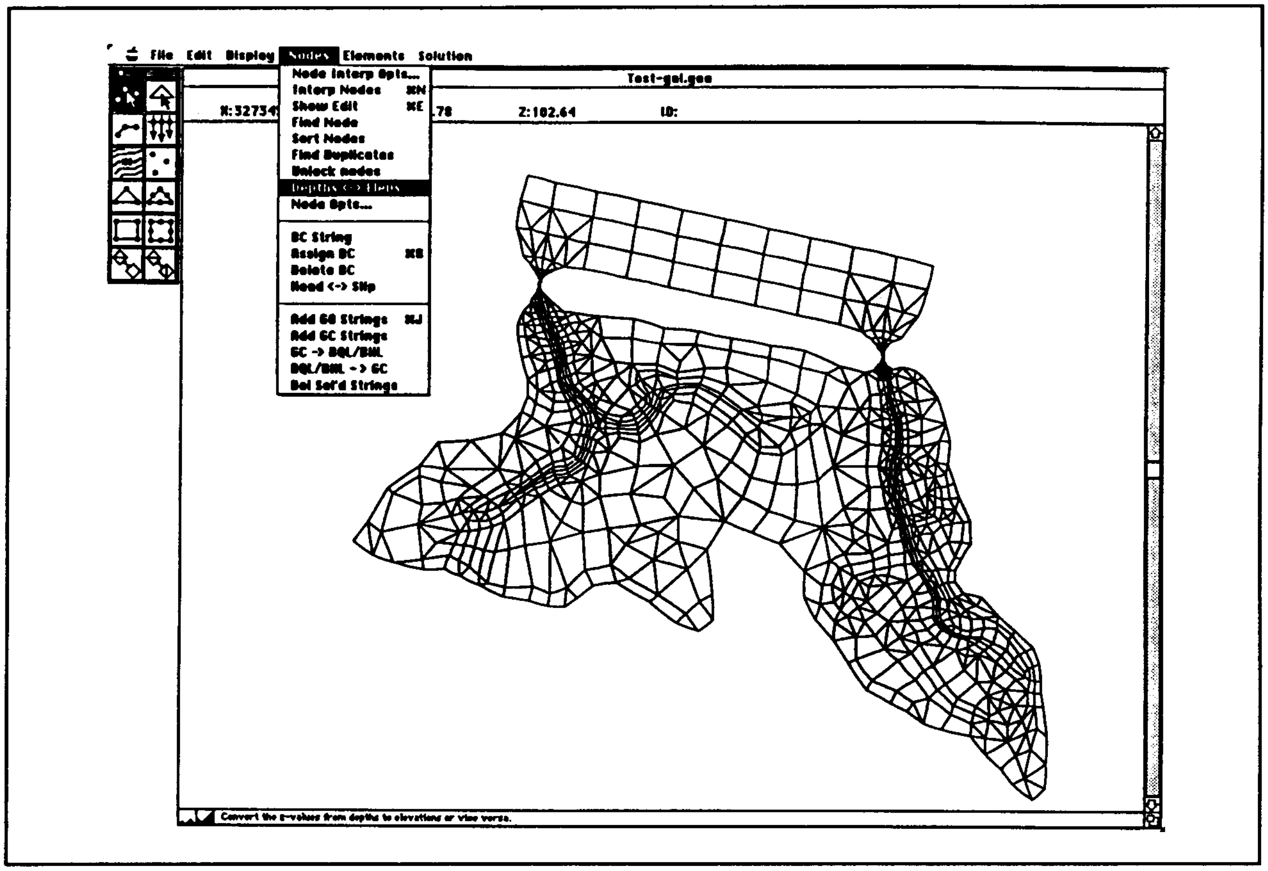

Figure 1. FastTABS Graphical User Interface showing Galilee Bird Sanctuary model mesh

by which hydrodynamic modeling could be accomplished for other renovated or created wetlands. Although each application involves tidal flows in estuarine wetlands, this application type is often more difficult than typical riverine applications. Therefore, the models can be used for most wetland problems.

The Bodkin Island wetland model provides an example of how future wetlands could be created since there is an abundance of clean dredged material in both rivers and estuaries. Bodkin Island is a one-acre island located in Eastern Bay which is a sub-estuary of Chesapeake Bay (Figure 2). Bodkin Island is subjected to accelerated erosion by wind waves and to a lesser extent, tidal currents. The proposed plan to save and expand Bodkin Island involved using clean dredged material and riprap to expand the island to six acres (Figure 3).

The island exterior was designed to be hardened against wave attack and the interior to provide nesting, shelter, and feeding areas for juvenile black ducks. This required designing ponds, intertidal marsh areas, and uplands in the interior. All of these geographic features were modeled hydrodynamically using FastTABS to ensure that wetting and drying of the interior marsh was accomplished as required for the plant and wildlife and that the newly created larger island did not adversely impact shellfish beds nearby. Typical results for a single time step are shown in Figure 4.

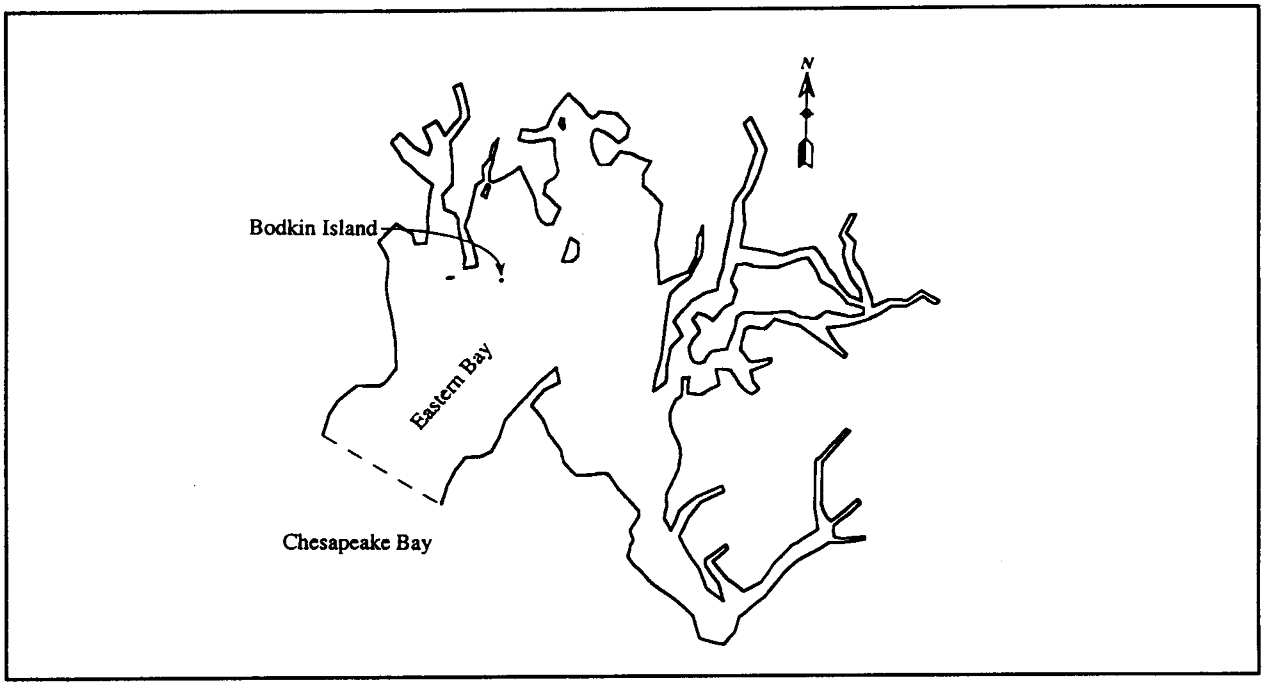

Figure 2. Modeled portion of Eastern Bay including Bodkin Island

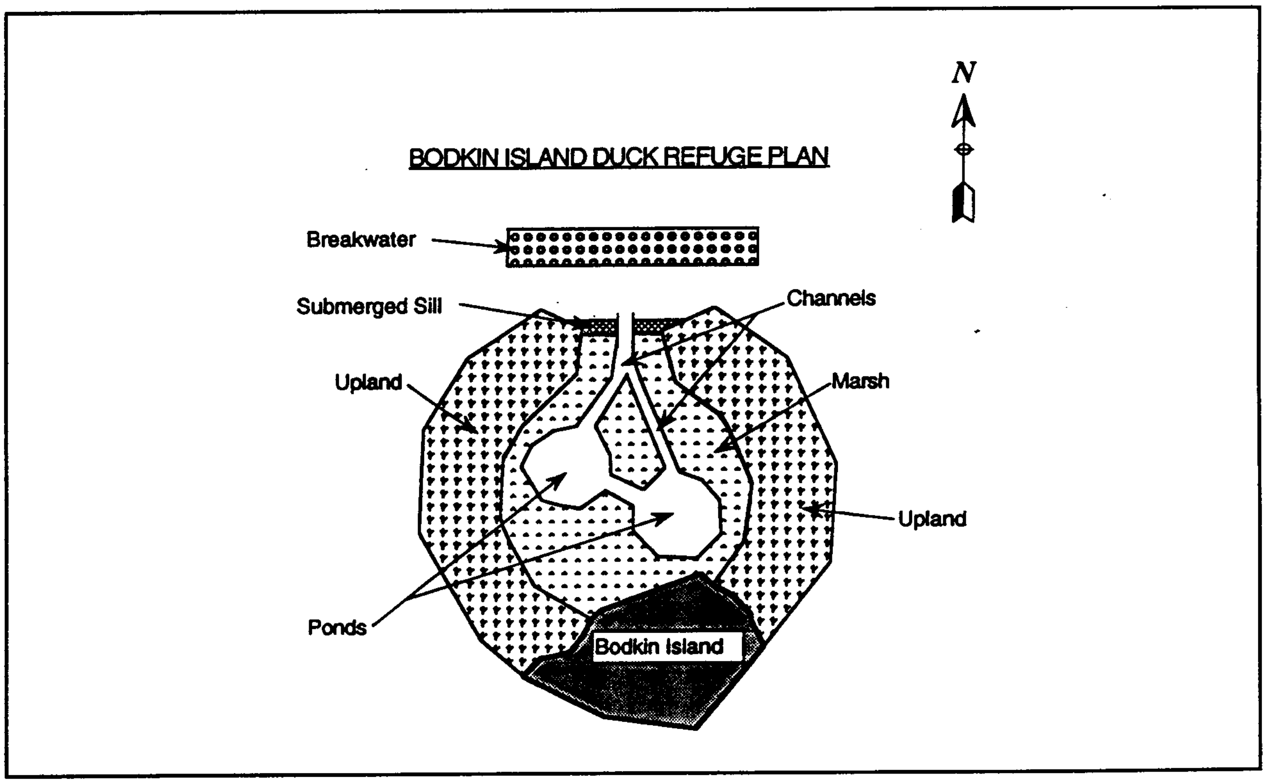

Figure 3. The proposed plan for Bodkin Island

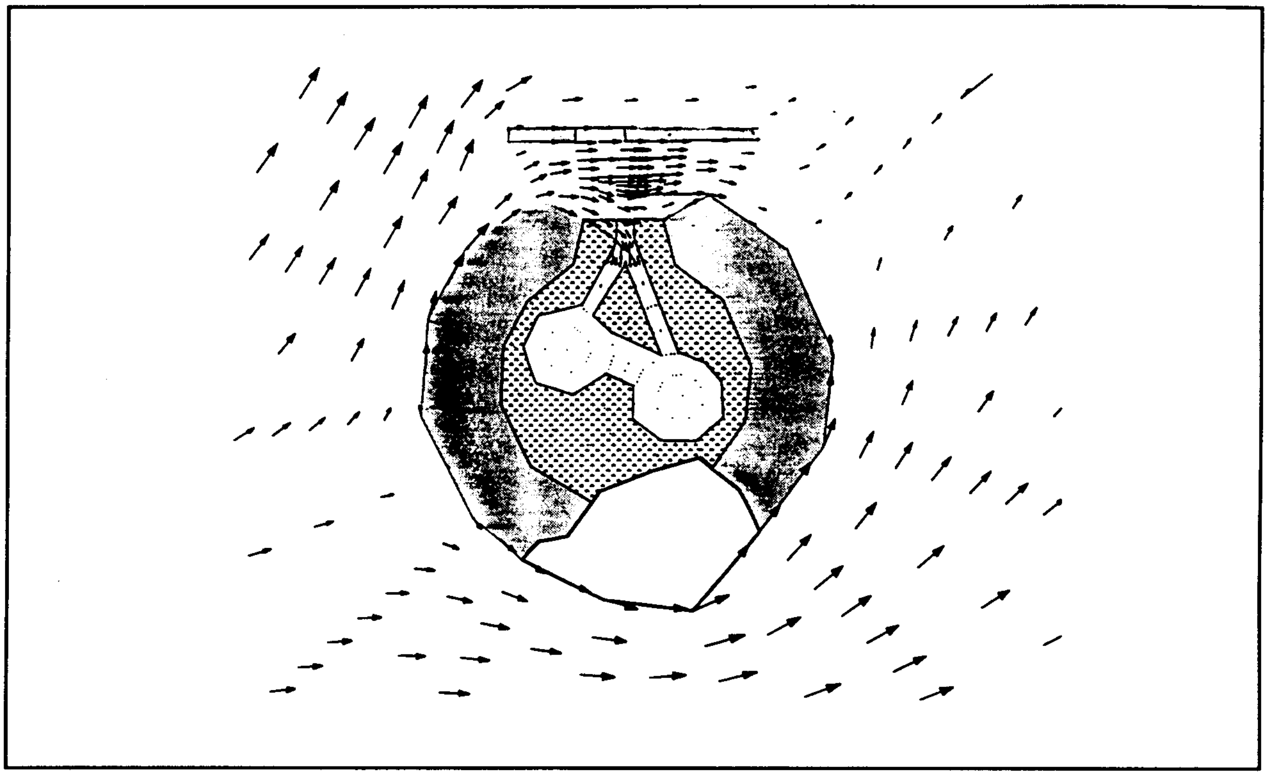

Figure 4. Bodkin Island velocity plot from FastTABS

The Galilee Bird Sanctuary is typical of many deteriorated wetlands. Previously, it was a brackish marsh until it was filled and cut off from tidal circulation by a road and undersize culverts. This application could be typical of many similar wetland renovation studies where brackish marshes are reclaimed from freshwater marshes created by manmade obstructions such as roads with undersized bridge openings or culverts.

In the Galilee application, FastTABS was used to determine the culvert size needed to provide sufficient circulation upstream of the culvert without causing scour problems in narrow channels within the renovated wetland. Figure 5 shows a velocity contour map that indicates the percentage of time the velocity magnitude exceeds 0.5 feet per second. It is apparent that velocities are much slower than those which would cause scour within the wetland. Figure 6 shows the wetted area within the marsh at high tide (max) and low tide (min). With each high tide, the entire wetland is exposed to brackish water. Previously, only a small area near the culverts was exposed to brackish water leaving the remainder wetted only by rain water. Figure 7 shows velocity vectors through one of the two culverts along with time histories of velocity and head (water surface elevation) at a selected point.

COMPUTER INFORMATION: The FastTABS software runs on Macintosh and DOS-based personal computers as well as most UNIX workstations. A primer, user's manual, and tutorial are available.

The FastTABS software was written by and is copyright to the Engineering Computer Graphics Laboratory of Brigham Young University in Provo, Utah, in cooperation with the Hydraulics Laboratory at WES. A limited government license allows Corps office use of the software supplied through WES. Other than Corps users may obtain the software from Brigham Young University, 801-378-5713.

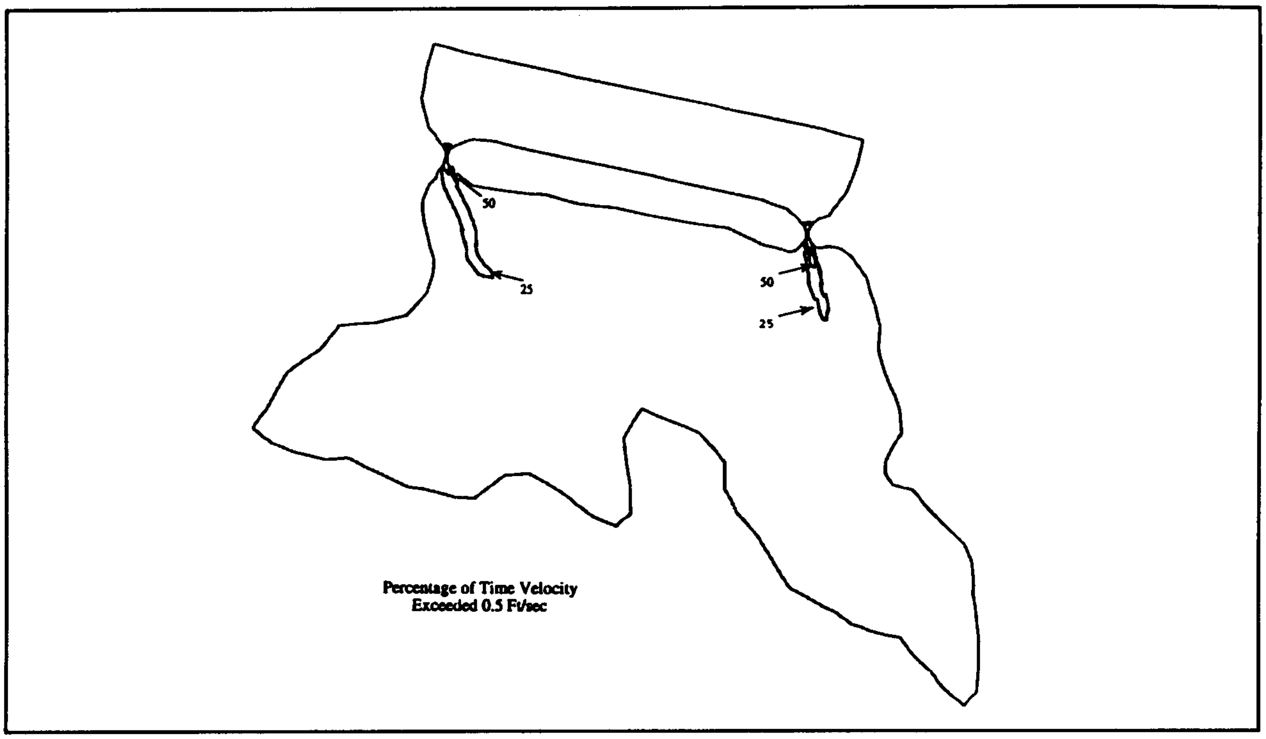

Figure 5. Galilee Bird Sanctuary current magnitude contours

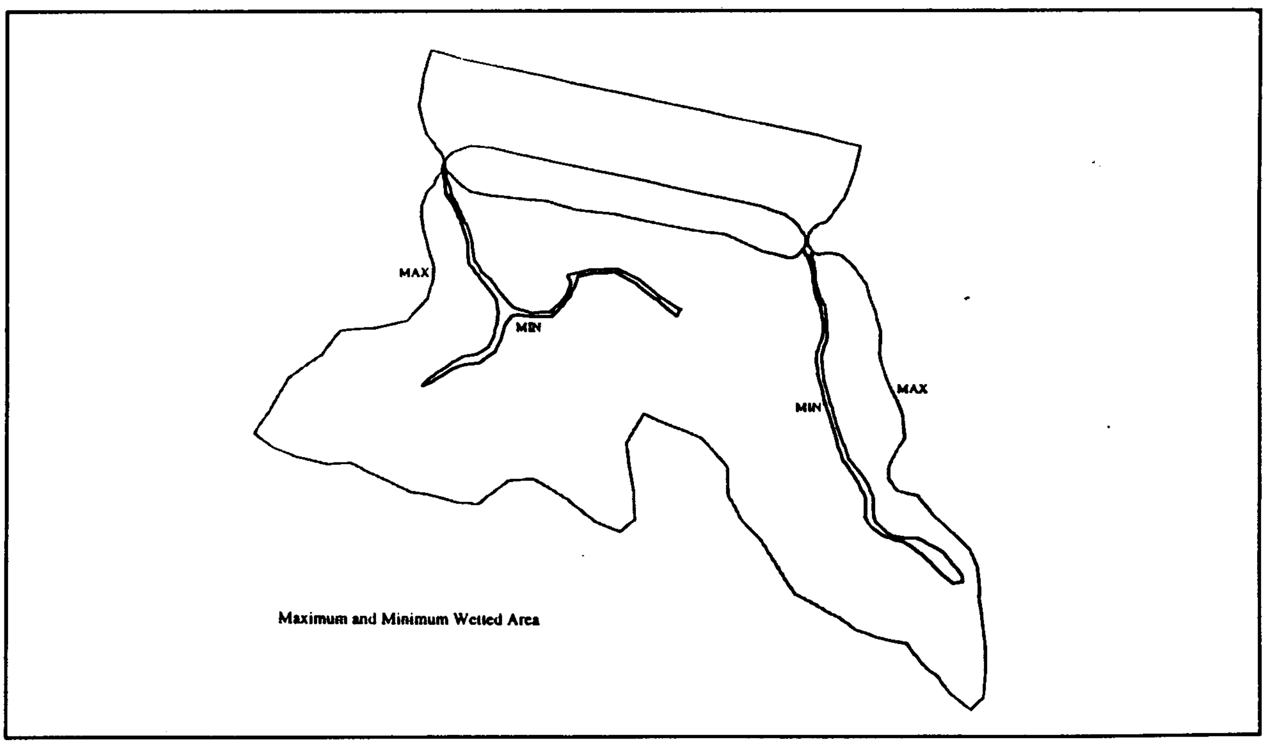

Figure 6. Galilee Bird Sanctuary maximum and minimum wetted area contours

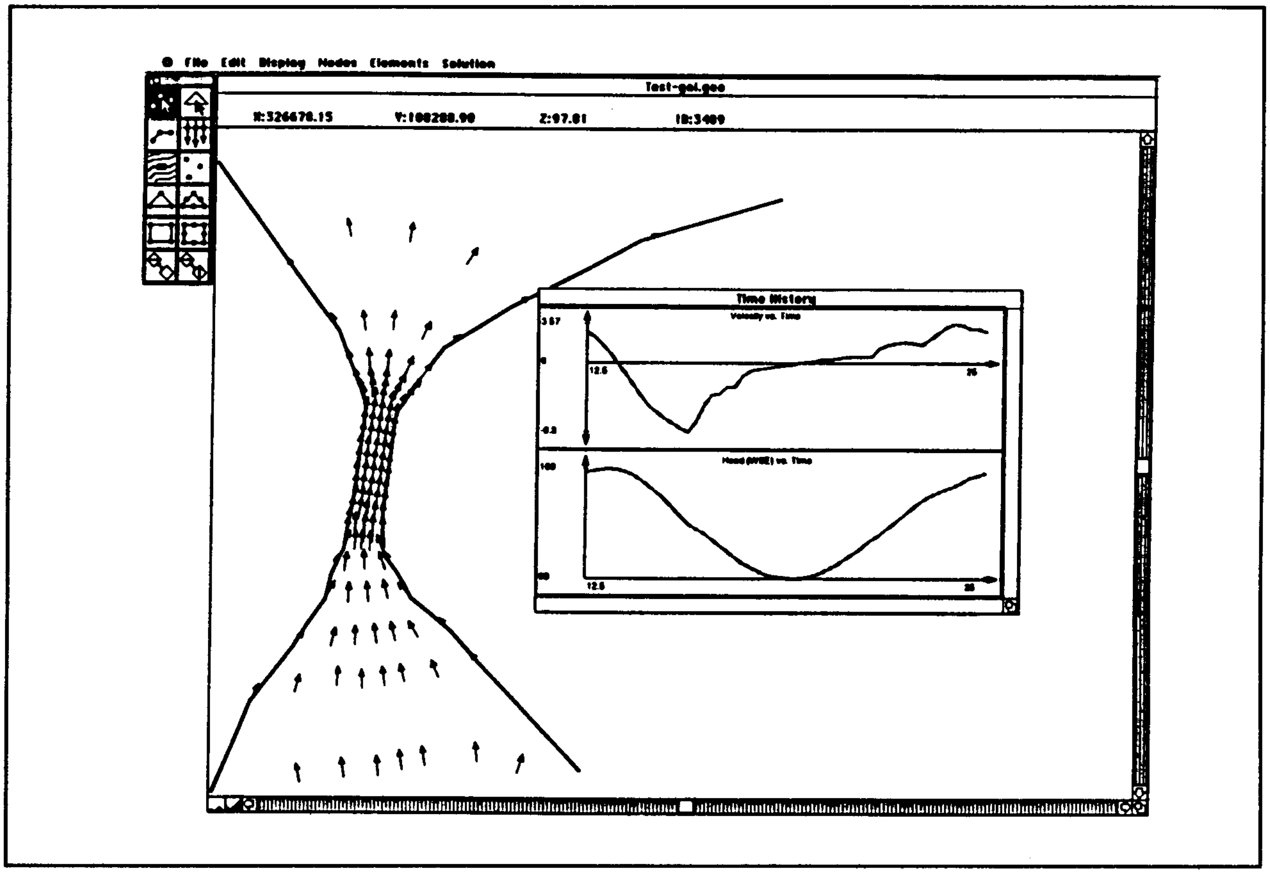

Figure 7. Galilee Bird Sanctuary velocity results near a culvert along with time histories of velocity magnitude and head

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Harmonic Analysis Can Assess Hydrologic Cumulative Impacts

PURPOSE: This technical note describes an aid for assessing cumulative impacts on wetlands. Harmonic analysis techniques are employed to reveal time-frames when disruption to basic flow patterns may have occurred.

BACKGROUND: Water-level patterns largely determine the nature of wetlands. Therefore, studies of historic water trends associated with wetlands should explain causes-and-effects operating on wetlands and the resulting landscape/ biotic composition. Keys to characterizing historic water-level trends are called "hydrologic indices."

SIMPLE INDICES SAMPLE: Hydrologic indices may be categorized as either simple or complex. Simple indices are easy to compute and include parameters such as mean, median, and range of flows. However, these indices often fail to describe adequately periodicity, seasonal behavior, or evolution of stream character resulting from land-use changes and channelization.

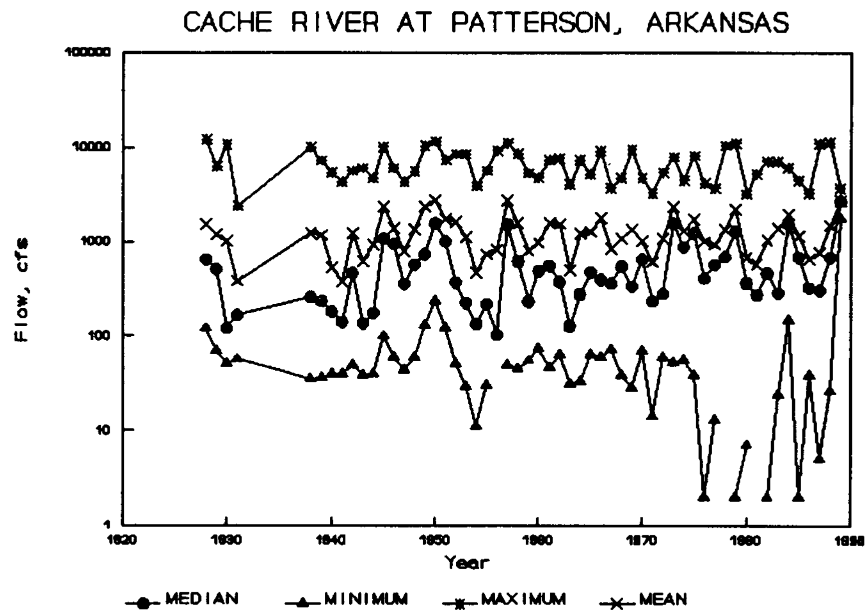
Despite obvious limitations, such simple indices can reveal important features of streamflow and how those parameters compare with those of other streams in the same basin. These simple indices can also give clues regarding the timing of historic, momentous events, such as the abrupt decrease of the monthly maximum flow in the Little Red River record (1961) shown in Figure 1 with records of other selected streams in the White River Basin (Arkansas/Missouri).

The effects of more subtle but perhaps no less profound impacts may be better detected and quantified using indices that are somewhat more complicated to derive but which may yield more insight into cumulative impact analysis. One such index investigated, harmonic analysis, is given here. Another index, time scale analysis, is treated in WRP Technical Note HY-IA-2.2.

HARMONIC ANALYSIS INDEX: Harmonic analysis can show not only periodicity but also the change of a stream's character ("flashiness," ratio of minima to maxima and means, etc.) over time. This index reveals seasonal aspects typical of streams where flow responds to snow melt, summer drought, and other seasonal events.

The flow record of the Cache River at Patterson, AR was examined using harmonic analysis. This record included partial or complete flow records for the years 1928 through 1931 and 1938 through 1989. In addition to stream gage records, this river and its basin have extensive historic land-use records as well as data gathered by the various remote sensing methods. Flowing through a wetland designated as one of profound importance (Kleiss 1993), studies of its hydrology and landscape ecology are ongoing. Therefore, new analysis techniques have a high potential for validation. Harmonic characteristics of the flow history of the Cache River are illustrated in Figure 2.

- The mean for each month in each time period ("decade") represented by the gage at Patterson, Arkansas, was determined. Because the record from 1921 through 1940 was available for only 12 years, this period was considered a "decade" for the purposes of this study.



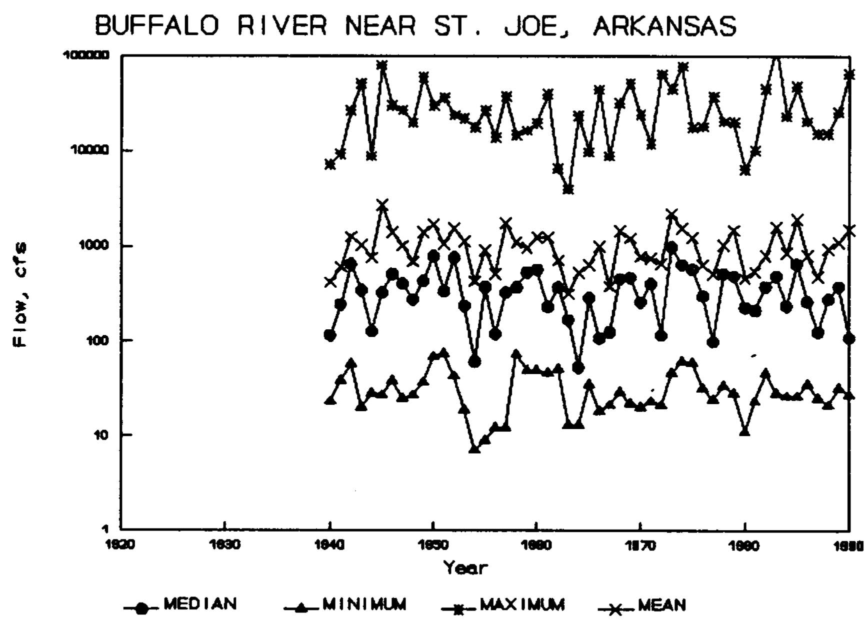
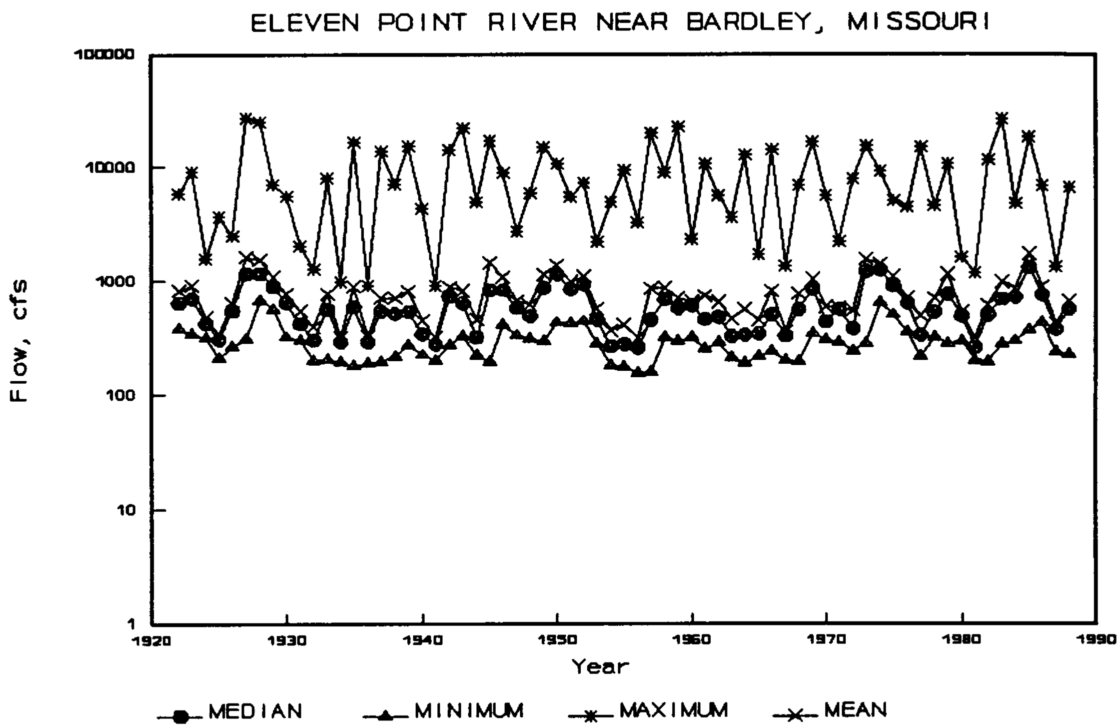


Figure 1. Yearly medians, minima, maxima, and means of selected steamflows in the White River Basin (Arkansas/Missouri). Note that the scale of flow is logarithmic and that recording periods do not include some years



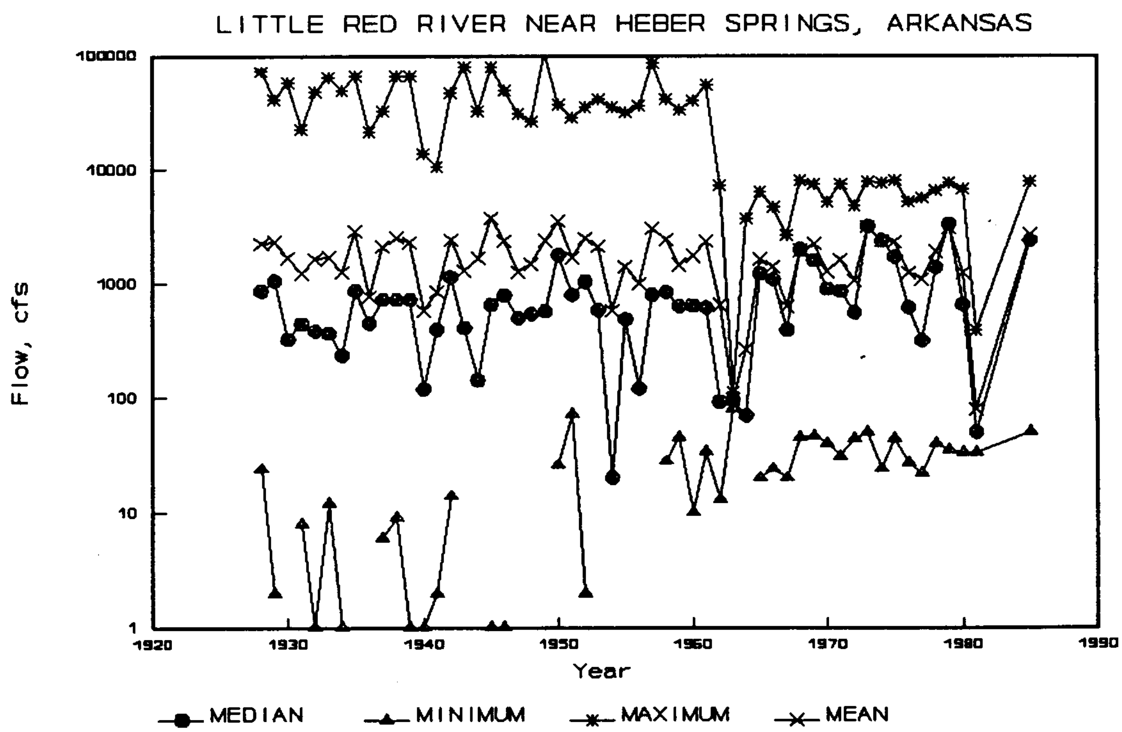


Figure 1. (Concluded)

- Of this resulting set of means, the mean, minimum, and maximum for each month in each decade were determined.

- Cosine curves were fit to the mean, minimum, and maximum values, respectively, for each decade using the PROC NLIN routine (SAS 1988).

- This procedure provided the coefficients (phase, amplitude) with period of one year used to produce the curves in Figures 2 to 5 corresponding to the respective months of the year.

Harmonic analysis also is convenient to compare flow patterns of rivers in the same or nearby watersheds, possibly permitting inference of regional or global effects. Figures 2 to 5 show results of the application of the harmonic analysis technique to the four streams presented in Figure 1. The minimum flow curves for each decade describing the Cache River reveal the progressive changes in both phase and amplitude, being conspicuous in the decade 1961-70. It should be noted that the cosine approximation may not always yield the "best" fit to the data compared to some other model.

In contrast, the harmonic analysis of the daily flow records of the Buffalo River (Fig. 3) reveals no similar deviation from the cosine function, while a corresponding analysis of the Eleven Point River (Fig. 4) shows a fairly consistent relationship between maximum means and means from decade to decade, with a "flatter" curve representing the minimum means in all decades but that of 1951-60. The record of the Little Red River (Fig. 5) reveals extreme fluctuation of the minimum monthly means until the decade of 1961-70, when the minimum curve became quite flat by comparison. These comparisons indicate that one or more fundamental changes occurred in the stream and/or basin either during the time period in question or in prior years (delayed effect) and these warrant further study. This easily observed phenomenon corresponds with the time of complete regulation of the stream to form Greers Ferry Lake, demonstrating the method to be sensitive to at least extreme events.

The ratio of the amplitude (estimated using PROC NLIN) to the corresponding mean (minimum, maximum, or median) of monthly flows for the time period of interest, can be used to summarize the strength of the seasonal pattern (*"seasonality index,"* modified from Nestler 1993). Higher values of this ratio indicate stronger seasonality in the flows, whereas lower values indicate unpredictability, or randomness, which is not necessarily dependent on season of the year. Figure 6 shows the Eleven Point River with low values of the index throughout its time period, whereas the values of the indices of the Cache River and the Little Red River generally decline with passing years. The seasonality indices for the maxima, minima, and medians are also shown to permit comparison of these statistics as well. Note that highest seasonality index values were obtained for the minima (compared to the other three statistics considered) for all streams except for the Eleven Point River.

CONCLUSION: Harmonic analysis is one technique for assessing cumulative impacts on wetlands. Streamflow (as well as groundwater) records available in many locales often span many years and may provide insight in definition of present wetlands whose current conditions have been dictated, at least in part, by these historic water conditions. In conjunction with land-use practice histories and remote sensing records of past conditions, these tools can contribute to cumulative impact analysis integral to overall planning, management, and protection of valuable and dwindling wetland resources.

Data provided by EarthInfo, Inc., US Geological Survey, and the US Army Engineer Districts were used in the formulation and validation of the techniques presented.

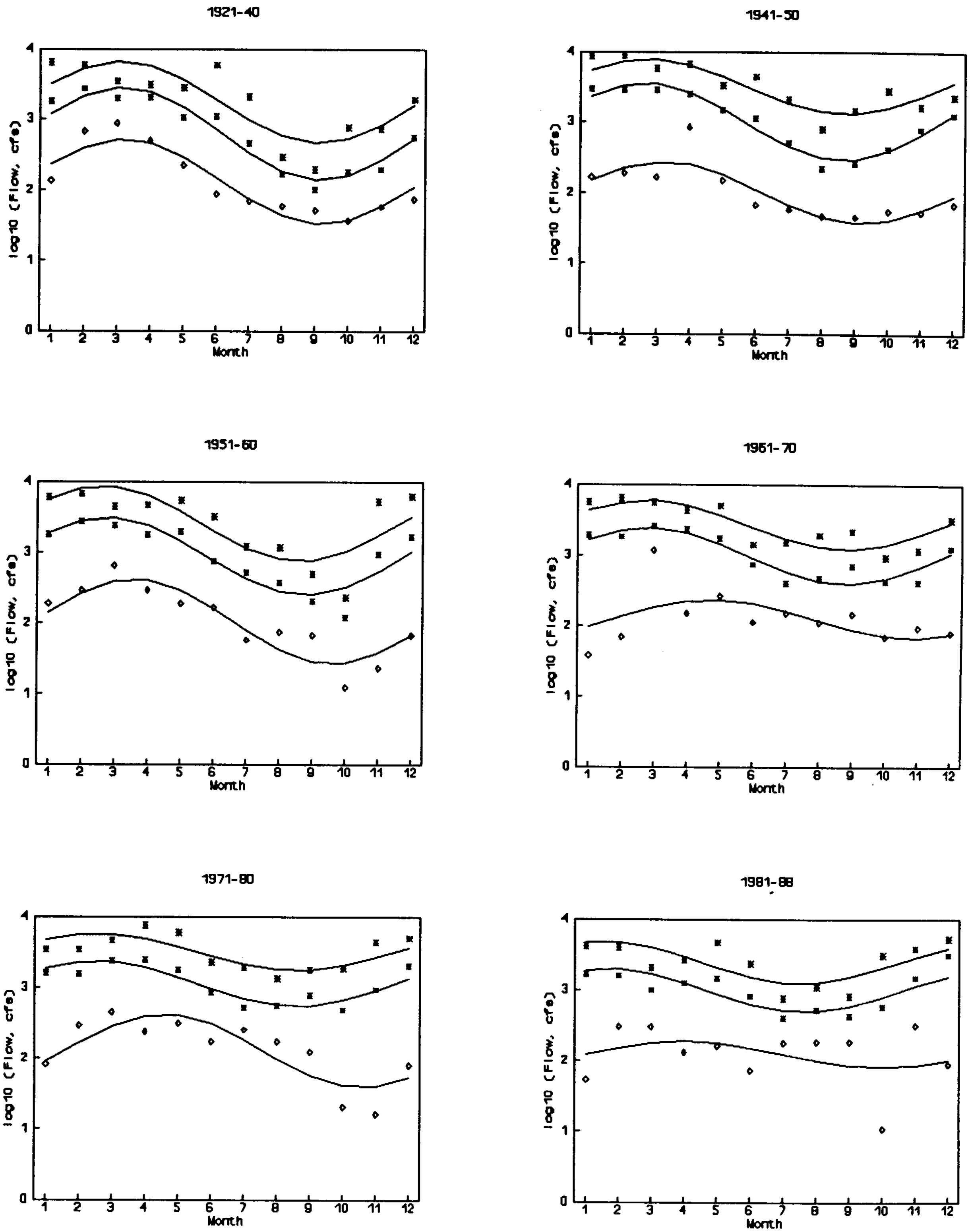


Figure 2. Harmonic analysis of the Cache River at Patterson, Arkansas

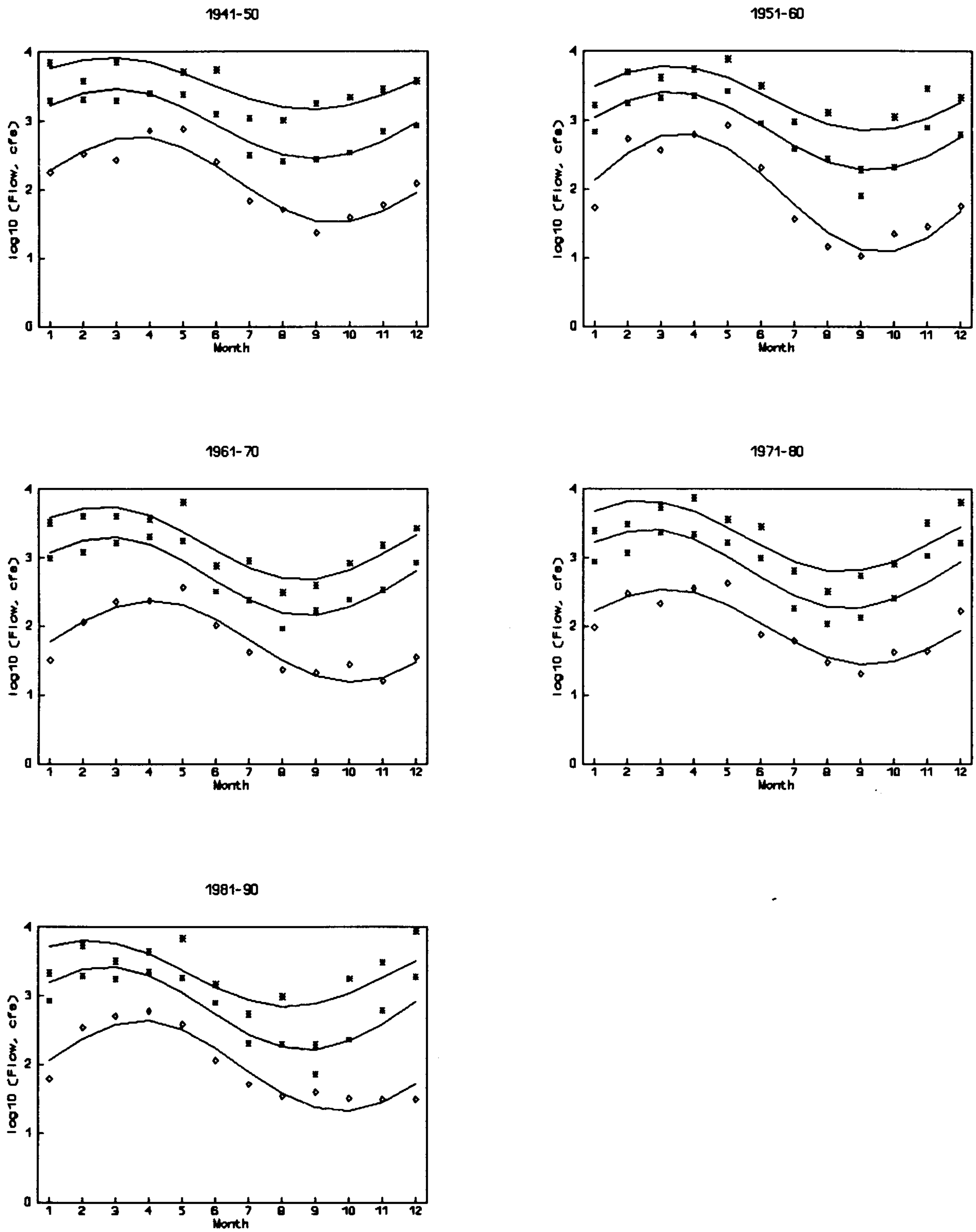


Figure 3. Harmonic analysis of the Buffalo River near St. Joe, Arkansas

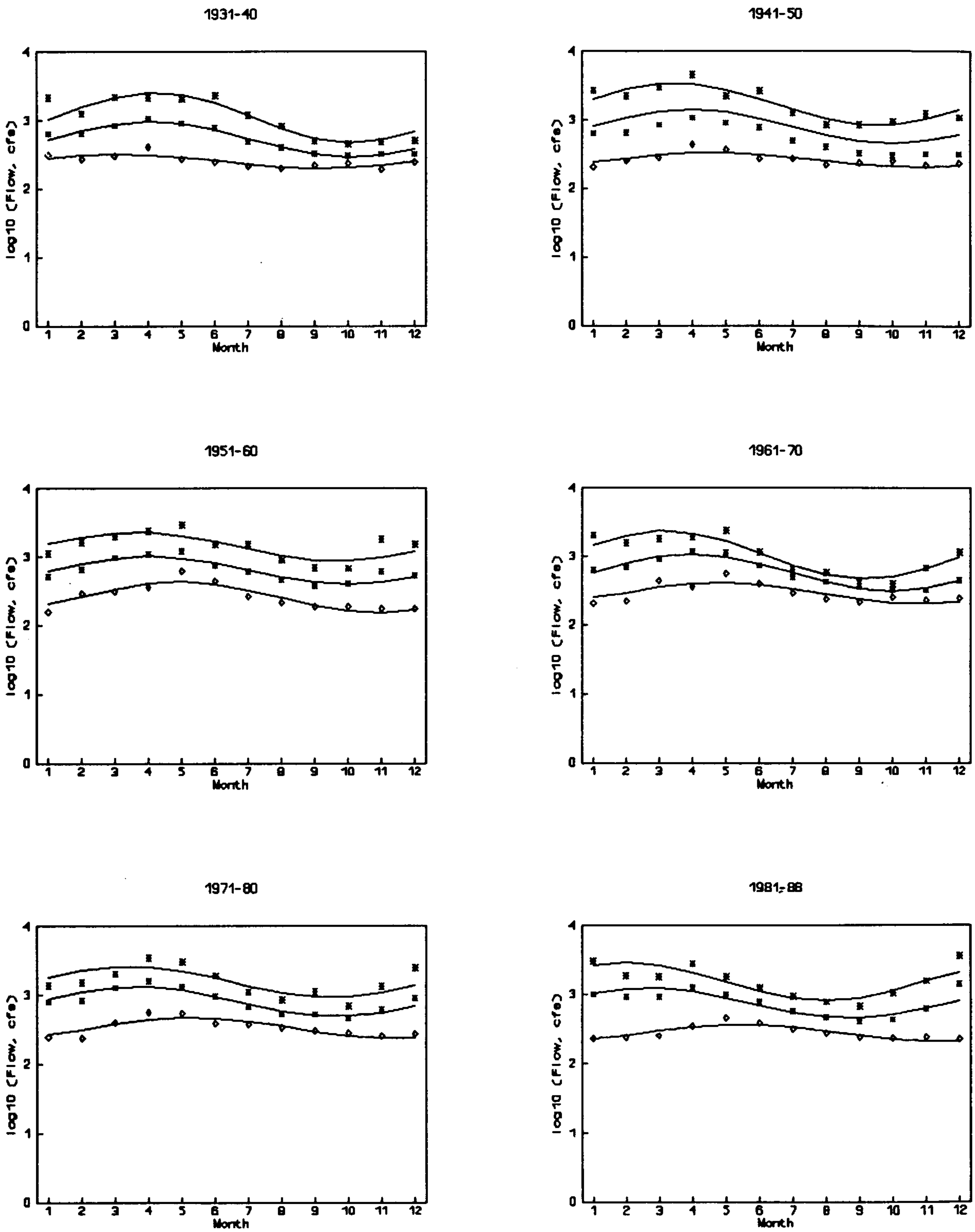


Figure 4. Harmonic analysis of the Eleven Point River near Bardley, Missouri

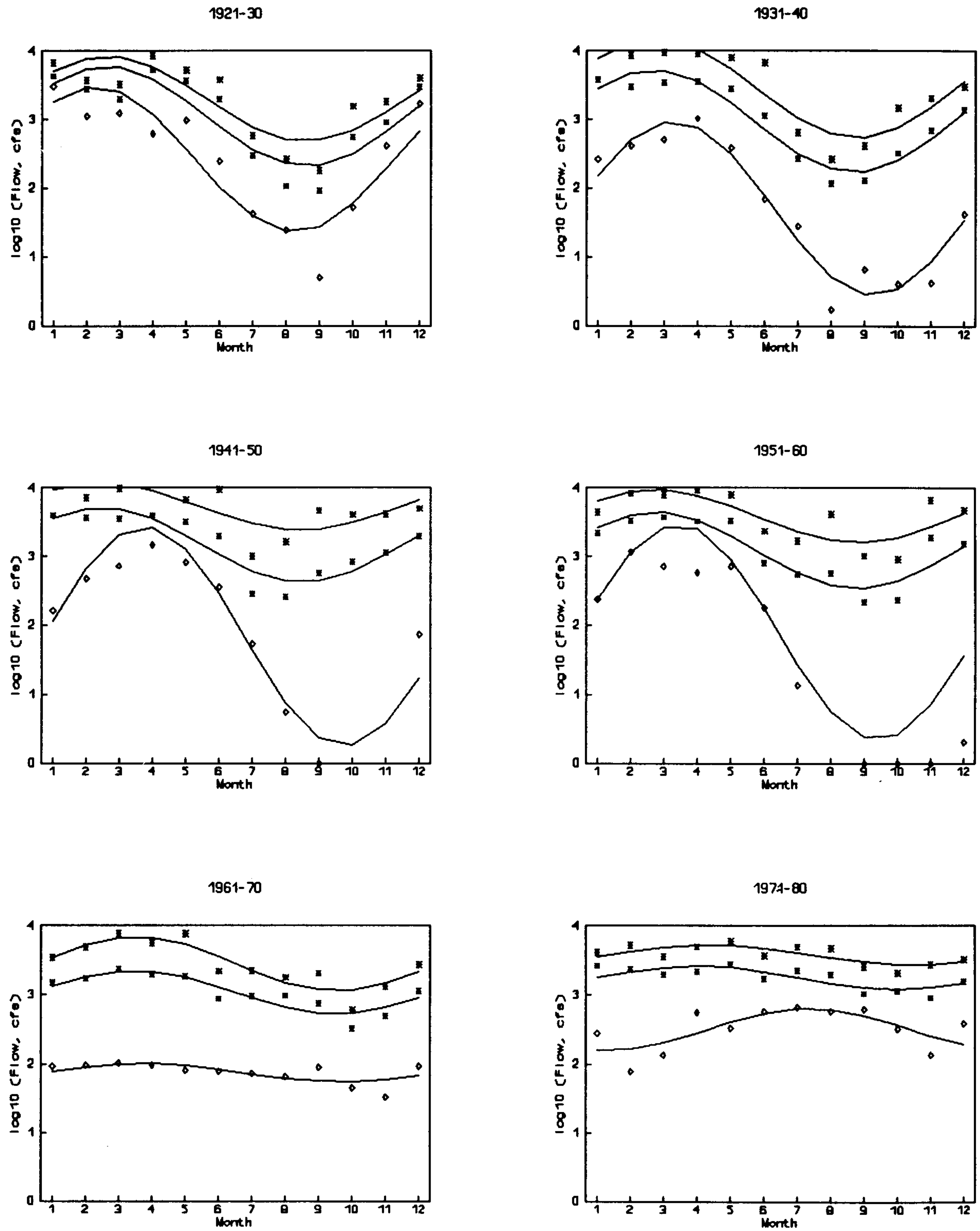


Figure 5. Harmonic analysis of the Little Red River near Heber Springs, Arkansas

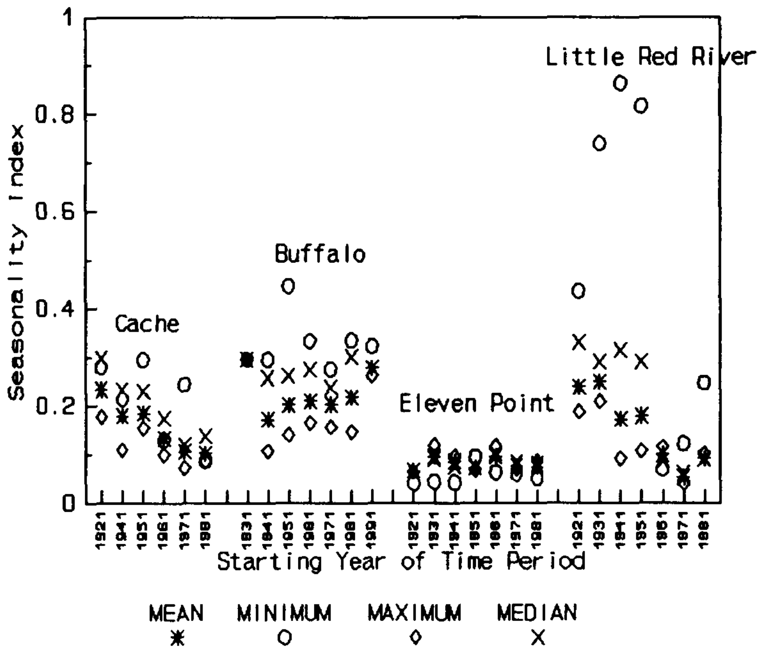


Figure 6. Seasonality indices of means, minima, maxima, and medians compared for four gages in the White River Basin, Arkansas/ Missouri

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WRP Technical Note HY-IA-2.2
May 1994

Time Scale Analysis Can Assess Hydrologic Cumulative Impacts

PURPOSE: This note describes an aid for assessing cumulative impacts on wetlands. Certain analysis techniques are employed to reveal time-frames when disruption to basic flow patterns may have occurred. This information is significant when attempting to perform cumulative impact analysis (CIA).

BACKGROUND: Water-level patterns largely determine the nature of wetlands. Therefore, studies of historic water trends associated with wetlands should explain causes-and-effects operating on wetlands and the resulting landscape/ biotic composition. Keys to characterizing historic water-level trends are called "hydrologic indices."

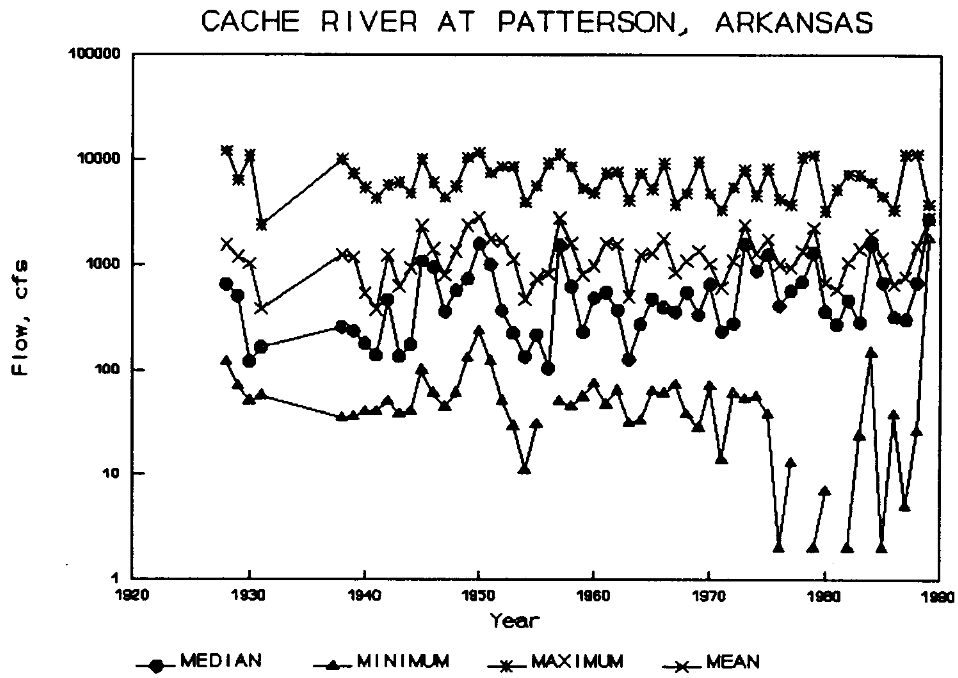
SIMPLE INDICES SAMPLE: Hydrologic indices may be categorized as either simple or complex. Simple indices are easy to compute and include parameters such as mean, median, and range of flows. However, these indices often fail to describe adequately periodicity, seasonal behavior, or evolution of stream character resulting from land-use changes and channelization.

Despite obvious limitations, such simple indices can reveal important features of streamflow and how they compare with those of other streams in the same basin. These simple indices can also give clues regarding the timing of historic, momentous events, such as the abrupt decrease of the monthly maximum flow in the Little Red River record (1961) shown in Figure 1 with records of other selected streams in the White River Basin (Arkansas/Missouri).

The effects of more subtle but perhaps no less profound impacts may be better detected and quantified using indices that are somewhat more complicated to derive but which may yield more insight into cumulative impact analysis. One such index, time-scale analysis, is given here. Another index, harmonic analysis, is treated in WRP Technical Note HY-IA-2.1.

TIME-SCALE ANALYSIS INDEX: Time-scale analysis compares relative "short-term" vs. "long-term" fluctuation in stage/levels of flow. This index relies on the theory of fractals (Peitgen and Richter 1986, Turcotte 1992), specifically that seemingly complex physical patterns such as daily stream flow vary in much the same way in a short period (few days) as in a longer period (many days)--the same shape is found at another place in another size. (The respective time periods are "self-similar").

An important fractal property, the fractal dimension, is commonly obtained using a "method of rulers." In this approach, progressively larger rulers are used to measure the perimeter of physical feature. A straight-line relationship between the common logarithm of both ruler length and perimeter is indicative of strong fractal properties. The slope of this line is termed the "fractal dimension." This relationship implies that a single underlying pattern is being repeated, but at different scales, within the feature.



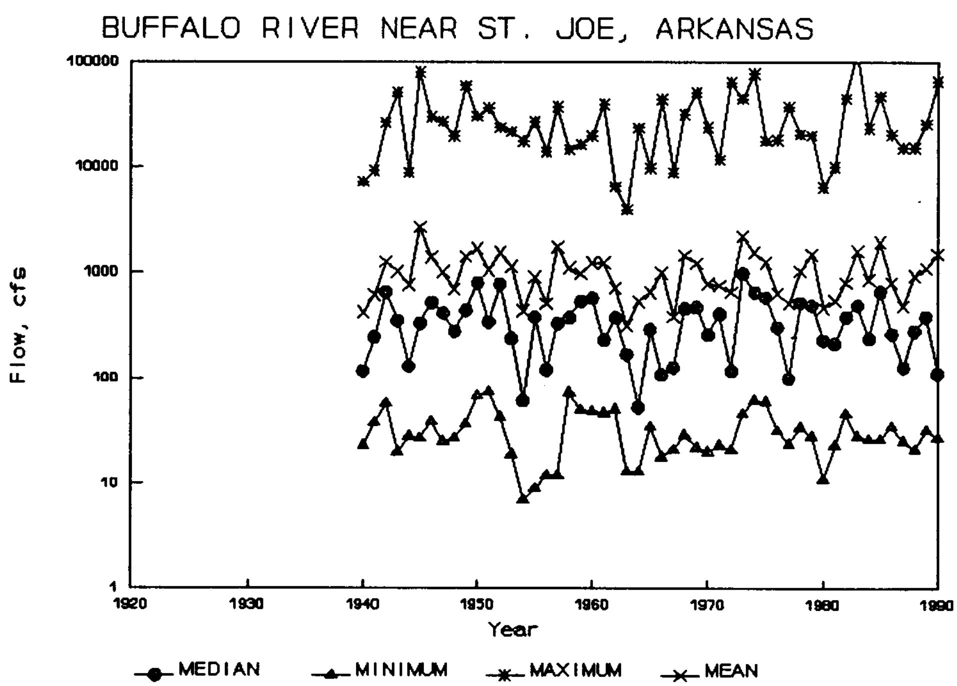
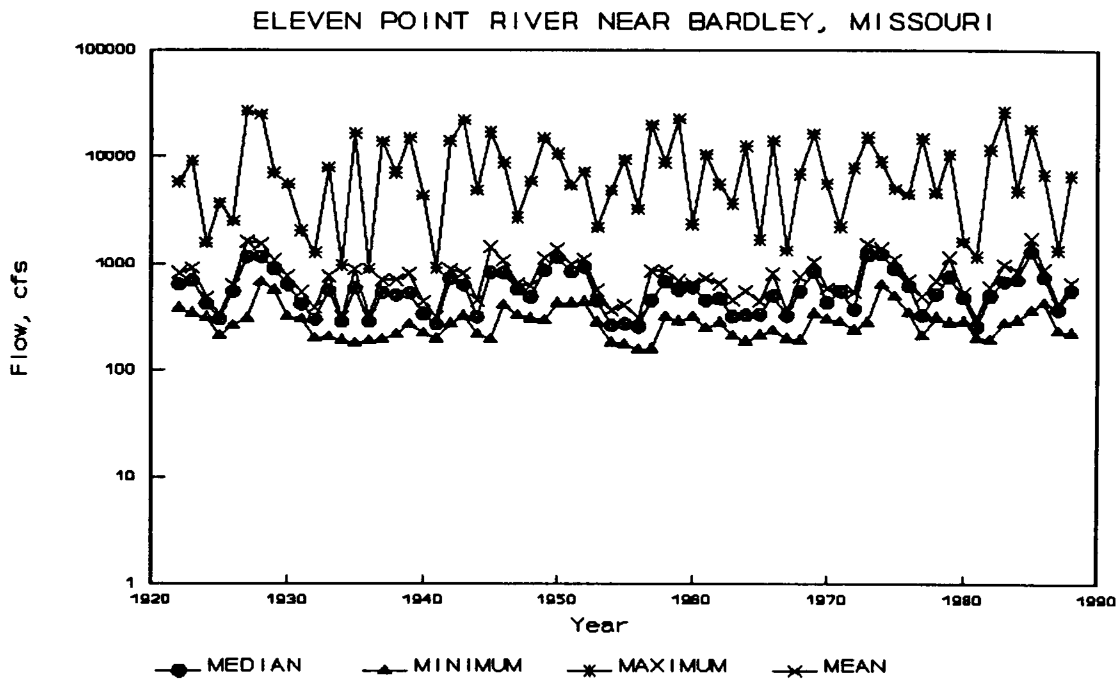


Figure 1. Yearly medians, minima, maxima, and means of selected steamflows in the White River Basin (Arkansas/Missouri). Note that the scale of flow is logarithmic and that recording periods do not include some years



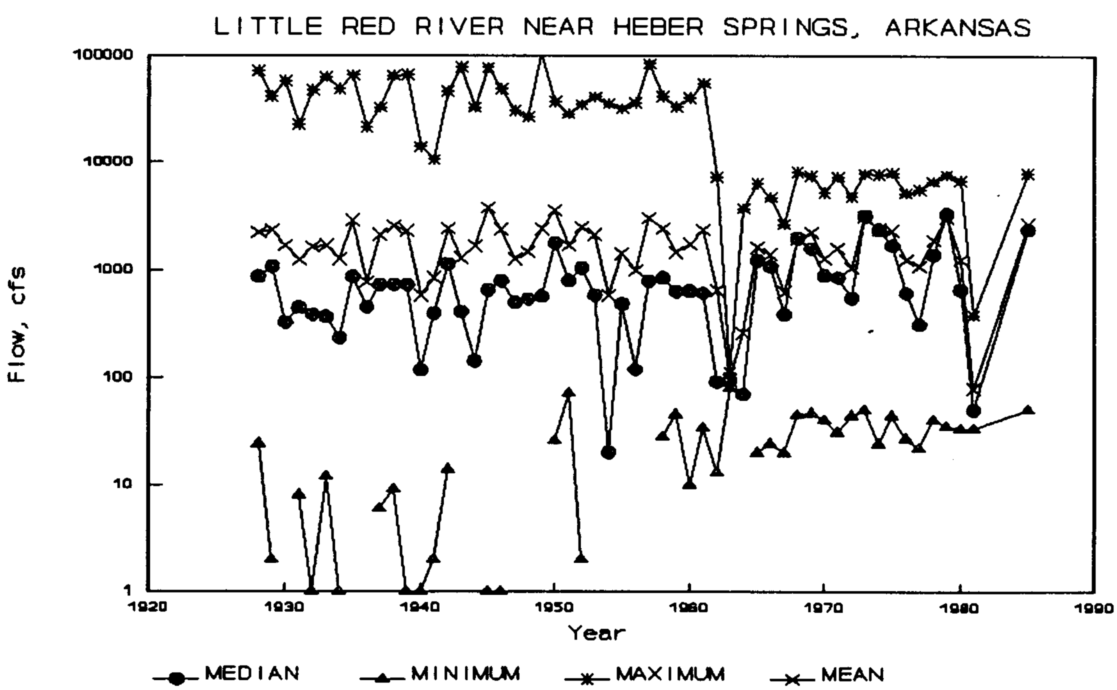


Figure 1. (Concluded)

Hydrologic time series are known to exhibit fractal properties (Changnon et al. 1991). For the Cache River application, these properties were described using discharge averages, "time dimension," based on different durations instead of rulers of different lengths, "distance dimension." The concept of evaluating information lost as a function of the resolution of measure is similar. Mean monthly flows were calculated for the period of record. Daily flows were then simulated by linear interpolation between adjacent months. The error between the synthesized daily flows based on monthly means (long-term) and the measured daily (short-term) flows represents primarily the contribution of hydrologic processes that occur at a duration greater than one day and less than one month. Examination of these errors between different basins or between different time periods at one site can provide insight into the dynamics of hydrologic processes that operate for a duration of less than one month.

The concept can be expanded to generate synthesized (simulated) daily flows based on many different time durations. The error between each of the synthesized daily flows and the measured daily flows represents the relationship between the different hydrologic processes that blend together to generate a hydrograph. Long-term trends in these errors indicate changes in the relative contribution of different hydrologic processes to the site hydrograph. As part of cumulative impact analysis, this information provides a partial hydrologic explanation for the results obtained using the simple indices and the harmonic analysis.

Complex hydrologic conditions can be quantified by using "root-mean-square error" (RMSE), resulting in measurement units identical to those of the original data, i.e., cubic feet per second (cfs).

Root mean square error (RMSE) calculated as

$$\mathrm{RMSE} = \left[\frac{\sum (S_{i+1} - S_i)^2}{\mathrm{NOBS}} \right]^{1/2}$$

where

S - (synthesized daily discharge based on successive time scales), and
NOBS - (number of observations)

is used to measure errors between recorded and synthesized daily flows based on different durations. By computing the RMSE of the same period lengths with individual daily flow values over decades, one can often identify the time frame in which some profound event affected flows.

Obvious departures from a prevailing trend can be observed in records of streams that have been impounded. For example, the Little Red River near Heber Springs or the Missouri River at Randall Dam (Fig. 2) had RMSE values that decreased markedly after the impoundment. In contrast, the RMSE of the low flow values (<200 cfs) of the Cache River at Patterson, *increased* considerably in later decades, implying a "flashier" (less damped flow) stream than was the case earlier in the century (Fig. 3). This information could provide an important clue regarding where, when, and what change(s) made the difference.

Behavior of the respective RMSE compared decade by decade for several different streams in a region may denote a localized or a global effect regarding short-term vs. long-term fluctuations in flow (Fig. 2). This tool may also be employed on certain flow levels, such as demonstrated with the

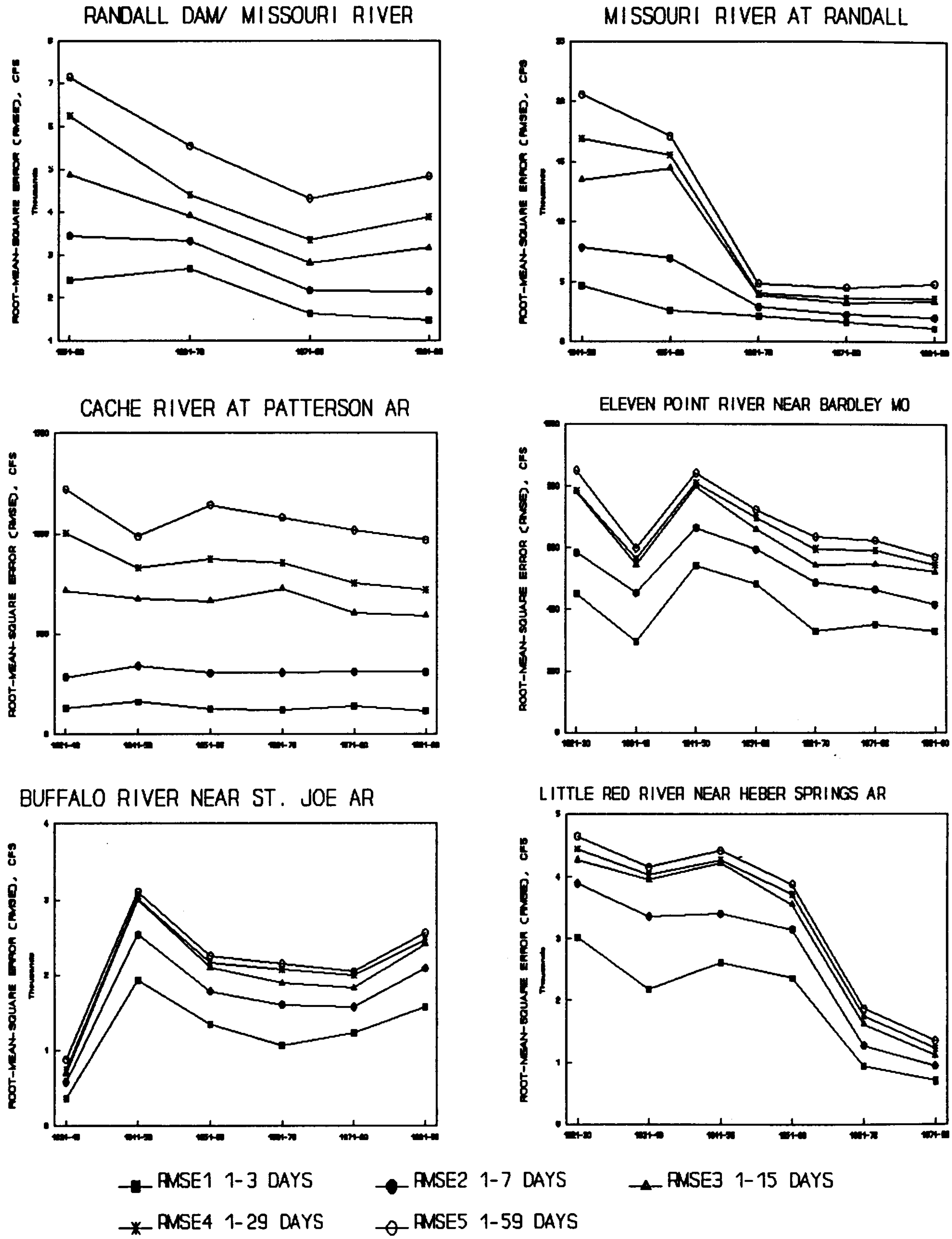
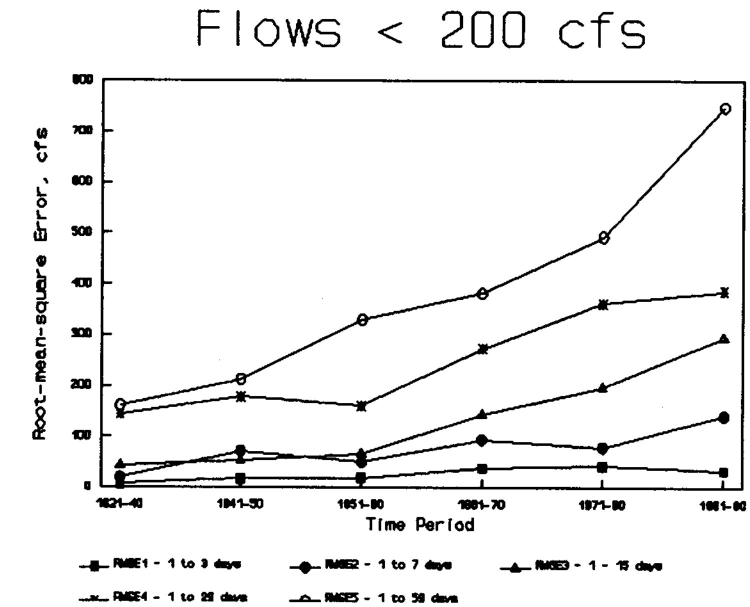


Figure 2. Comparison of respective root-mean-square errors (RMSE) of streams examined with time-scale analysis



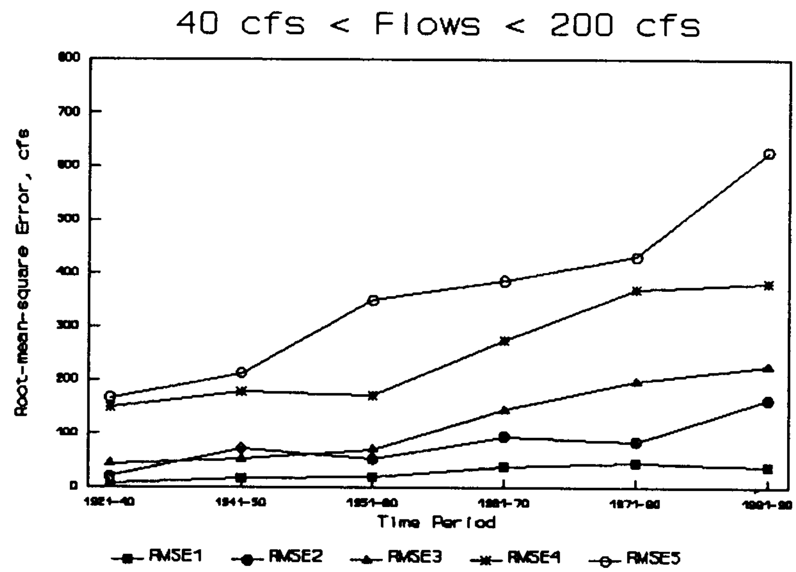


Figure 3. Comparison of root-mean-square error (RMSE) of flows less than 200 cfs of the Cache River at Patterson, Arkansas, with (above) and without (below) flows less than 40 cfs to investigate effects of different recording methods

Cache River flow records (Fig. 3) to explain changes in the lower ranges of flows when level of base flow is of primary interest, e.g., the maintenance of a groundwater level necessary for a particular wetland. No significant changes in the nature of stream flow should yield similar RMSE's for each of the time intervals (days). Additionally, time-scale analyses allow looking at the possible effects of differing recording methods on overall flow analyses. With the recent advent of unattended, automatically recording gages, there might be reason to suppose that more recent measurements might be considered more reliable than earlier ones. Upon examining the record of the Cache River at Patterson, it was observed that low flows seemed to be set at a default value of no less than 40 cfs. Hence, one analysis excluded values less than 40 cfs to see if this suspected "artifact" affected overall results. Examining records with errors summarized and compressed such as one may see in Figure 3 reveals only slight deviation in RMSE when recorded values less than or equal 40 cfs were deleted. Thus, even if the values had been estimated, the effect on results was minimal given the expanse of the study of low flows of the Cache River at Patterson, AR. Simple linear regression on the respective RMSEs of the sets with and without lower values, were correlated.

CONCLUSION: Time-scale analysis is a technique offering promise for assessing cumulative impacts on wetlands. Streamflow (as well as groundwater) records available in many locales, often spanning many years, may yield up a treasure of clues defining present wetlands whose current conditions have been dictated, at least in part, by historic water conditions. In conjunction with land-use practice histories and remote sensing records of present and past conditions, these tools can contribute to cumulative impact analysis integral to overall planning, management, and protection of valuable, dwindling wetland resources.

Data provided by EarthInfo, Inc., U.S. Geological Survey, and the U.S. Army Engineer Districts were used in the formulation and validation of the techniques presented.

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Future Needs in Wetland Hydrology and Hydraulics

PURPOSE: Future research needs are identified for improving computer simulations of wetland hydrology and hydraulics. Potential applications of modeling to determine simplified techniques and relationships are also provided.

MODEL IMPROVEMENTS: The Wetlands Dynamic Water Budget Model (WDWBM) was based on a number of models in common use and incorporates many of these models' theories and approaches. An underlying objective was to keep the model relatively simple and efficient, so that it could simulate year-to-year variations. While many of the future model modifications will arise from applications, several areas of study have been identified to improve model accuracy, efficiency, and reliability.

The current version of the vertical processes module uses a Priestley-Taylor (1972) description of evapotranspiration. This procedure requires knowledge of only air temperature and net solar radiation. More sophisticated methods for estimating evapotranspiration could be examined to assess their effectiveness and data requirements. The vertical processes module assumes a saturated flow condition for infiltration across the ground surface. A more exact physical description of unsaturated infiltration could be incorporated into the model.

A number of methods can be used to determine hydraulic conductivity when simulating groundwater flow. It would be useful to examine the effects of these methods on model results. An explicit solution algorithm has been used for all modules. It would be useful to examine the potential computation savings and effects on model accuracy of using an implicit algorithm for at least the vertical processes module, which can have the most severe stability constraints. Model geometry could be calculated using a digital elevation model, from which the nodal and link properties could be determined.

Future Applications: To date, the WDWBM has been successfully applied to riverine and estuarine wetlands. As a consequence, it is felt that the surface water routines have been adequately verified. In order to more completely test the accuracy and adequacy of the remaining process modules, wetlands characterized by primary interactions between horizontal groundwater flow, infiltration, and evapotranspiration need to be examined. An excellent example of such wetlands are the prairie potholes on the northern plains. Finally, the interactions between all the modules can be studied by applying the water budget model at the landscape or watershed basinwide level. At this level, the relative importance of each of the water budget components will vary both spatially and temporally.

Simplified Methods: The successful application of the WDWBM to the Black Swamp area of the Cache River in Arkansas (Figure 1) has produced a 4-year database of surface water elevations and flows throughout the wetland. This database, along with field data collected during the Wetlands Research Program, provides the opportunity to develop and test simplified methods of wetland hydrology and hydraulics (H&H) analyses. For example, correlation functions of computed surface water elevations with available U.S. Geological Survey (USGS) gauge data at Patterson, James Ferry, and Cotton Plant can allow future evaluation of the impacts of flow alteration on the hydroperiod within the Black Swamp, and development of a historical database of hydroperiods using the long-term gauge record available at Patterson. Several examples of these regressions are provided in Walton and others (1995).

Regression of the Patterson gauge versus the B5 gauge, using a 2-day time lag, is presented in Figure 2. A companion analysis of hydroperiod (continuous days above a specified flood stage) at the Patterson gauge is compared with the resulting stage-duration at the B5 gauge in Table 1.

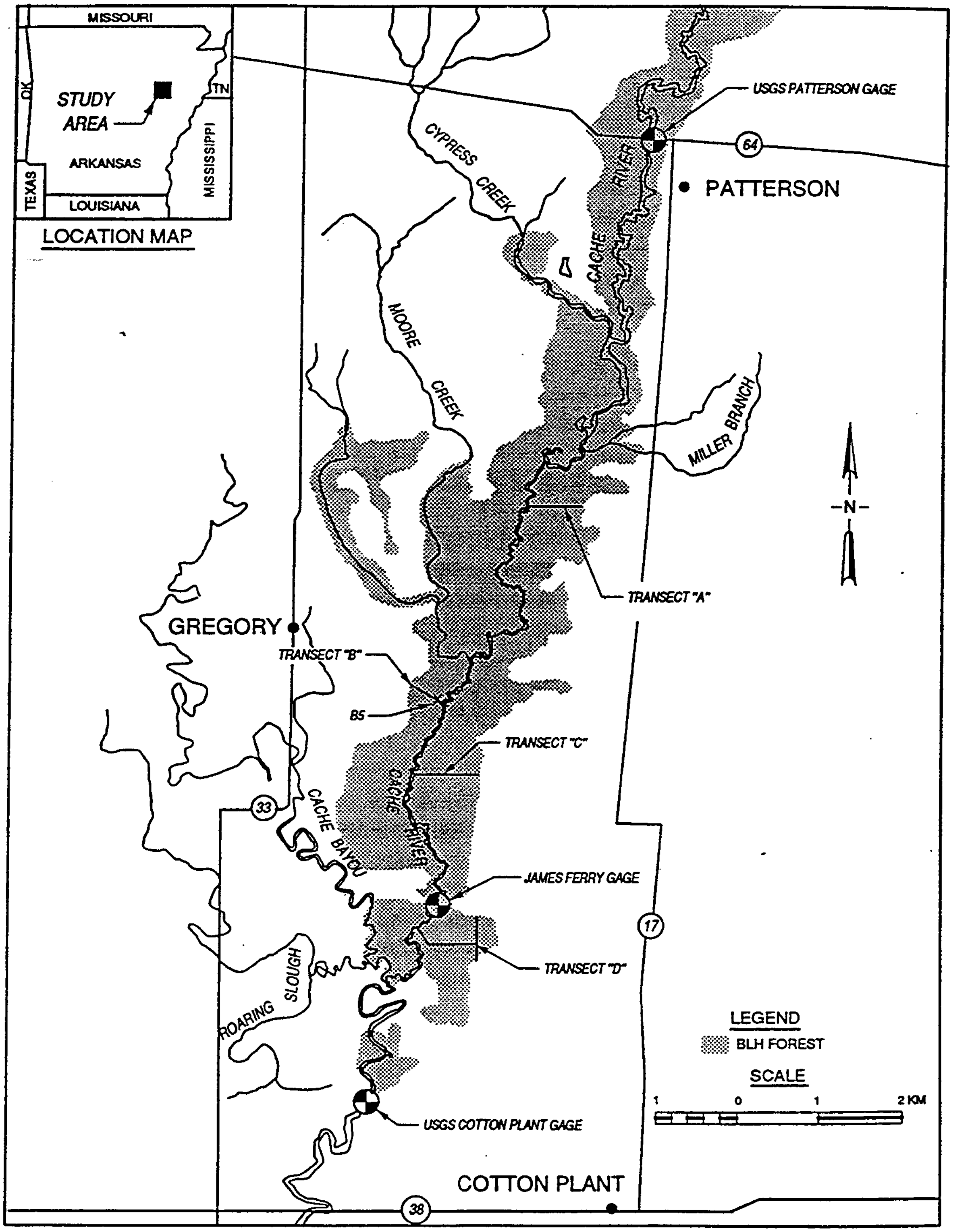

Figure 1. Black Swamp Wetland on the Cache River in Arkansas

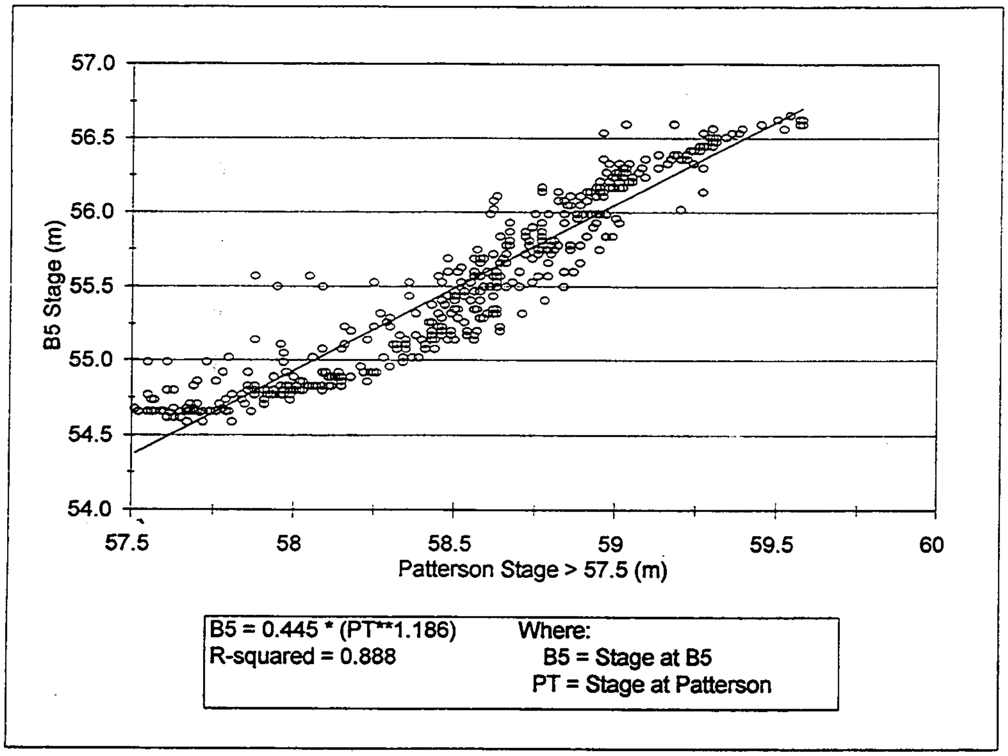

Figure 2. Regression analysis between Patterson and B5 data using a 2-day time lag

Table 1
Hydroperiod at Station B5 and Patterson

B5			Patterson		
Elevation, m	**Days**	**Mean**	**Elevation, m**	**Days**	**Mean**
54.6	511	170	56.7	510	510
54.8	382	42	57.8	379	31
55.0	303	60	58.2	300	33
55.2	258	43	58.5	249	24
55.4	221	36	58.5	218	18
55.6	175	29	58.7	171	17
55.8	134	26	58.8	129	16
56.0	102	25	58.9	100	16
56.2	57	14	59.0	50	10
56.5	23	11	59.3	19	6

Examination of this table suggests that there is a consistent correlation between the hydroperiod of a given storm event recorded at Patterson and the resulting stage and hydroperiod experienced at the B5 gauge. In addition, there is significant backwater or storage effect due to the constriction of the flow between James Ferry and Cotton Plant. This is seen in the increased hydroperiod at the B5 gauge. The important point to be made here is that the computed surface elevation database can be used to develop similar correlation functions at any location within the Black Swamp. As a result, more complete and longer term information on stage and hydroperiod at the other three Cache River research transects can be made available.

A simplified method for performing a wetlands water budget analysis and determining the relative importance of H&H processes can be based on the following balance equation:

$$Q_i + R + G = Q_o + ET + I \tag{1}$$

where

Q_i = surface water flow into system
R = direct rainfall on wetland
G = groundwater discharge to wetland
Q_o = surface water flow out of system
ET = evapotranspiration from wetland
I = infiltration to the groundwater

For many wetlands, these variables can be estimated using simple methods or available data, or both. Surface water inflows can be determined from upstream gauges or from published statistics of river flows. If the basin is ungauged, then it is possible to estimate flows using data from nearby gauged basins and multiplying by the ratio of drainage basin areas, or using published regression analyses (available for many states from the USGS). Downstream flows can be determined using the same approaches, or by using data from control structures such as weirs, gates, and culverts. Flows can be converted to annual volumes/unit area by summing the flow over 1 year and dividing by the surface area of the site.

Rainfall data are available from nearby gauges or published summaries (for example, annual rainfall maps from the National Oceanic and Atmospheric Administration). Potential evapotranspiration data can be obtained from a number of sources or calculated from atmospheric parameters such as air temperature and net solar radiation, using formulas such as the Priestley-Taylor method.

Groundwater discharge can be estimated from potentiometric head data using Darcy's Law. Maximum potential infiltration can be estimated from percolation tests, sometimes published in local soils reports, or from measurements or estimates of saturated hydraulic conductivity based on only a crude knowledge of local soil types. An upper bound can be calculated by multiplying one-half times the saturated hydraulic conductivity by the amount of time the site is estimated to be inundated or receiving rainfall. It should be recognized that this may represent an extreme upper bound as it does not consider other factors, such as the soil becoming fully saturated and unable to receive additional water unless some soil water is removed. It is also important to recognize that Equation 1 can be used to estimate the magnitude of a process with no data, or to provide an alternative estimate for a process (usually groundwater discharge or infiltration) that may be poorly estimated, provided estimates are available for ***all*** of the other processes.

To decide whether each process is important in the hydrology of the wetland being evaluated requires a knowledge of the errors in these estimates and a decision as to when one process dominates another. Typically, riverflows can be measured to 5 to 10 percent accuracy if good gauge data are available. Measurements and estimates of the other variables are probably less accurate in most cases. A first-order criterion might be that one process is not significant if it provides less than 10 percent of the flow of any other component.

To illustrate this procedure, the Cache River database was used to develop an approximate annual water budget (Table 2).

Table 2
Annual Water Budget for the Black Swamp Wetlands

Variable	Annual Volume/Unit Area, m
Inflow	14
Outflow	16
Rainfall	1
Evapotranspiration	1
Groundwater discharge	<1
Infiltration	<1

Infiltration was estimated at about 6 m, assuming reasonable values for saturated hydraulic conductivity and inundation of the wetlands about one-third of the time. However, this value is probably greatly overestimated, as it neglects the saturated soil conditions that would frequently result under these conditions. Therefore, a more reasonable value, shown in Tables 1 and 2, was used based on satisfying the water budget of Equation 1. From this analysis, using a 10-percent criterion, one could conclude that on an annual-average basis, only river inflows and outflows are of major hydrologic importance in the Black Swamp. This analysis could be expanded to consider the relative importance of processes at other time scales (perhaps seasonal) and to examine other types of wetlands.

CONCLUSION: Future research needs have been presented which would improve upon the predictive capability of the WDWBM. In addition to describing potential model improvements and future applications, a guide has been presented for using the water budget model as a test platform for the development and verification of simplified methods of wetland H&H analyses. Examples of simplified methods for 1) determining stage and hydroperiod throughout the Black Swamp of the Cache River and 2) performing approximate water budgets for wetlands and determining the relative importance of individual H&H processes have also been presented.

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WRP Technical Note HY-IA-3.1
August 1993

Installing Monitoring Wells/ Piezometers in Wetlands

PURPOSE: Wetland regulatory personnel frequently need quantitative information about shallow hydrologic regimes of wetlands and adjacent uplands. Monitoring wells and piezometers are some of the easiest instruments to use to determine depth of shallow water tables. Most of the literature on piezometers and monitoring wells, however, deals with installation to greater depths than needed for wetland regulatory purposes. This technical note describes methods of construction and installation of monitoring wells and piezometers placed at depths within and immediately below the soil profile using hand-held equipment.*

DIFFERENCE BETWEEN SHALLOW MONITORING WELLS AND PIEZOMETERS: Monitoring wells and piezometers are open pipes set in the ground. They passively allow water levels to rise and fall inside them. The difference between a monitoring well and a piezometer is where along the pipe water is allowed to enter (length of perforated area).

Shallow monitoring wells allow penetration of water through perforations along most of the length of the pipe below ground. Therefore, the water level in a monitoring well reflects the composite water pressure integrated over the long, perforated portion of the pipe. This kind of well sometimes is called an "open-sided well," "observation well," or a "perforated pipe."

Piezometers allow penetration of water only at the bottom of the pipe, either directly into the bottom or along a short length of perforation near the bottom. Consequently, the water level in a piezometer reflects the water pressure only at the bottom of the pipe. Piezometers are sometimes called "cased wells."

The difference between monitoring wells and piezometers is significant because monitoring wells generally extend through more than one water bearing layer and therefore cannot be used to detect perched water tables, whereas piezometers can. Water pressures in the soil vary in response to several factors, including depth, differential permeability of strata, and water flow. These different factors can be isolated and interpreted independently with groups of piezometers. These factors cannot be differentiated with a monitoring well because different water pressures are intercepted at many depths within the same instrument and cannot be sorted out.

SELECTING INSTRUMENTATION: Before installing instruments, it is vital to define study objectives to avoid gathering unnecessary or meaningless data.

To investigate when a free water surface is within the top foot or two of the soil, 2-ft deep monitoring wells are sufficient. Deeper instruments are not necessary and may yield misleading information if improperly chosen and situated.

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* The methods described herein do not apply to water-sampling studies. Researchers needing to sample water from wells should refer to U.S. Army Corps of Engineers Document EM 1110-7-1(FR): Monitor Well Installation at Hazardous and Toxic Waste Sites and ASTM D5092-90: Design and Installation of Ground Water Monitoring Wells in Aquifers.

When trying to characterize water flows into and out of a wetland or differences in water pressure of soil horizons, clusters or "nests" of piezometers are needed. Most mitigation and evaluation studies require nests of piezometers with instruments located at depths ranging from a couple to many feet. Each piezometer in a nest should be installed at the same surface elevation and within a couple meters of the others. This arrangement allows answering questions about ground-water discharge and recharge, direction and rate of water flow, and water flow in different strata.

Zones of possible perching or water flow must be identified after study objectives are determined. This requires soil profile descriptions to the depth of interest -- often 6 to 10 ft. The profile descriptions should include horizon depths and information from which significant differences in permeability can be inferred: texture, induration, and bulk density.

If only shallow monitoring wells are used, they should be placed above the first slowly permeable horizon that could potentially perch water. Piezometers, on the other hand, should be installed both above and below horizons of low permeability to verify perching. Sand strata should also be monitored. Instruments should not be located at uniform depths around a study area unless the soils are uniformly stratified.

Typical well configurations include a shallow monitoring well through the A and E soil horizons and piezometers in the B horizon and C horizons. Deeper piezometers are often included, particularly if there are significant changes in grain size distribution in the lower soil profile. Soil studies usually include piezometers to 80 inches, the arbitrary lower depth of soil characterization in most parts of the country. Soil profile characteristics are available from the USDA Soil Conservation Service.

CONSTRUCTION OF PIEZOMETERS AND SHALLOW MONITORING WELLS: Monitoring wells and piezometers consist of four parts. Starting from the bottom and working up, these are (1) the well point, (2) the screen, (3) the riser, and (4) the well cap (Fig. 1). Other items that may be used in installation include (5) sealant to prevent water flowing along the sides of the pipe, (6) sand to ensure hydrologic contact and to filter out fines that move toward the well, (7) filter sock of geotextile to further filter out fine materials, and (8) concrete protection pads.

- The well point keeps soil from entering the well from the bottom. This may happen by sloughing during periods of high hydraulic head, particularly in sands and highly dispersive soils. Well points are bought separately if the wells are constructed of PVC pipe. One should drill holes or saw a slit in the bottom of a commercially manufactured well point to prevent the closed well point from holding water and giving false readings during drought.

- The screen allows water entry into the sides of the pipe. In shallow monitoring wells the screen extends from the bottom of the pipe to within 6 in. of the ground surface. In piezometers, the screen is the perforated end of the pipe, usually 6-12 in. in length.

  Commercially manufactured PVC well screen consists of finely slotted pipe. Screen with 0.010-in. width slots is adequate for most situations. In dispersive soils with high silt contents one should use 0.006-in. slots and a sand pack of 40-60 mesh silica sand.

  The slot size of the well screen should be determined relative to the grain size analysis. In granular non-cohesive strata that will fall in easily around the screen, filter packs are not necessary. The slot size should retain at least 90-99% of the filter pack (ASTM D-5092-90).

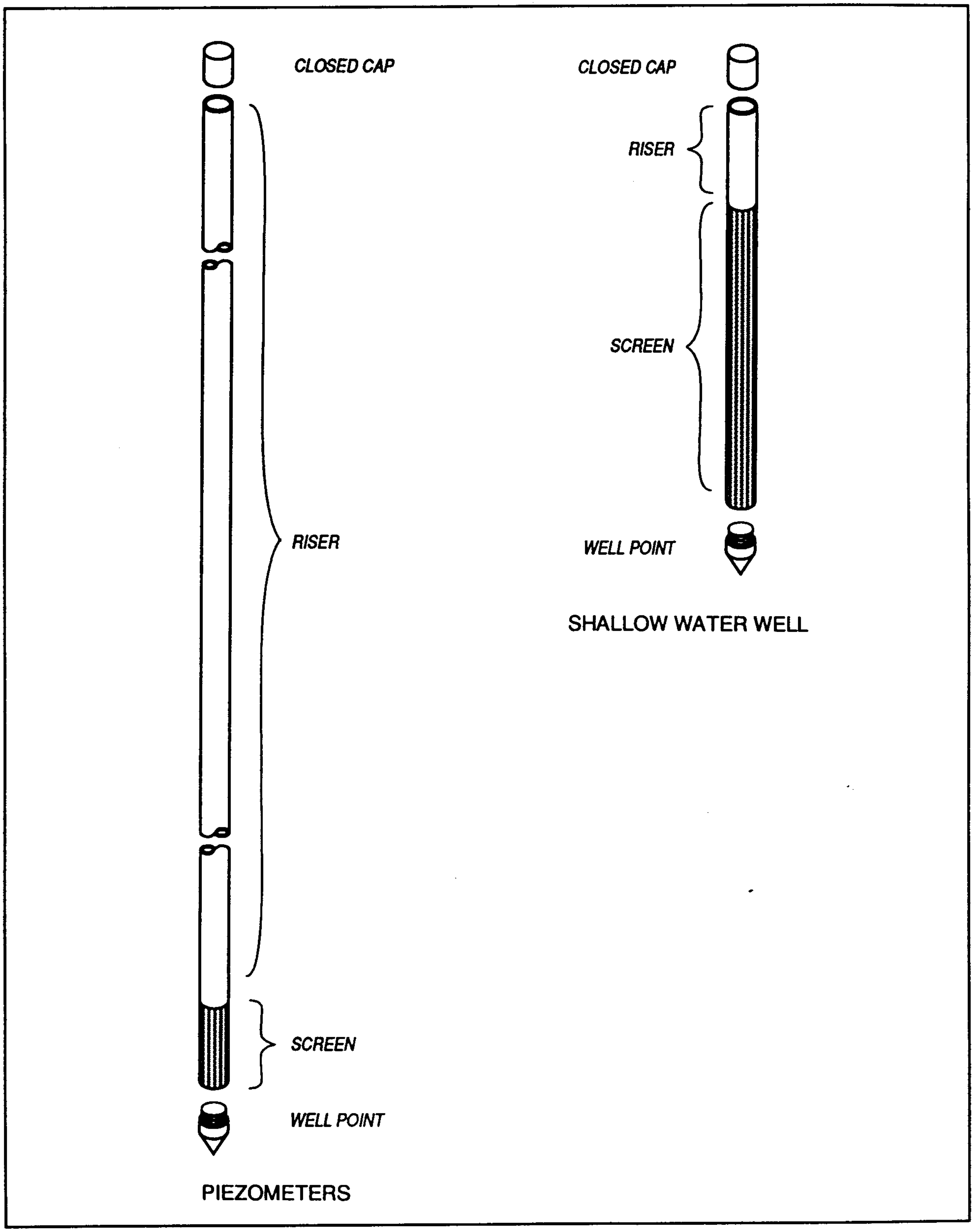

Figure 1. Parts of piezometers and shallow monitoring wells

- The riser is unslotted pipe that extends from the top of the screen through the ground surface and into the air to allow monitoring access. Riser of PVC is sold separately from the screen in 2 to 15 ft lengths. Sections of PVC riser may be screwed together to extend the riser to the length desired.

  The diameter of pipe used in piezometers and shallow monitoring wells depends on the purpose of the well and monitoring devices used. Pipes with an inside diameter (ID) of 1 in. or less are preferred. Small water samplers and automatic monitoring devices are available to be used in the small diameter pipes. If not, larger diameter pipe will be necessary, the size depending on method of sampling or monitoring.

  In shallow monitoring wells the riser should extend from 6 in. below the ground surface to the top of the pipe above ground. In piezometers the riser extends from the monitoring depth to the top of the pipe. Height above the ground surface depends on local needs such as visibility and access. Shallow pipes should not be extended more than a couple feet above the ground surface because of the great leverage that can be applied to the above-ground riser.

- The well cap is placed on top of the pipe to protect the well from contamination and rainfall. Well caps should fit tightly enough that animals cannot remove them and should be made of material that will not deteriorate with exposure to the elements. Threaded PVC caps meet these requirements in commercially bought wells.

  Well caps can be easily constructed from PVC pipe of larger inside diameter than the outside diameter of the piezometer. The larger ID pipe is cut to 6-in. lengths; one end of the 6-in. cylinder is then closed by gluing on an appropriately sized PVC cap (Fig. 2). Inverted plastic bottles or tin cans should not be used because of the ease with which they can be removed by animals or wind and because many such objects rust, degrade in sunlight, or break when frozen.

  Well caps should allow air pressure inside the pipe to equalize with that outside. Some PVC well caps are manufactured to allow air passage through a joint. Others should be modified so they cannot be threaded on tightly; this modification can be accomplished by closing the lower part of the threads with a bead of epoxy. If a vent hole is drilled in the side of the riser it should be too small for wasps to enter.

  After reading, well caps should not be secured so tightly that the shallow pipe must be pried and jostled to remove the cap. If surface water may overflow the tops of the pipes, caps should be secured so they will not be lost.

- Sealant is placed above the sand filter. This prevents water flow along the sides of the pipe from the ground surface and through channels leading to the pipe. If the well screen is below the water table at time of installation, the annular space above the sand is filled with bentonite to the top of the water table; grout is used to fill the annular space above the water table and to the soil surface. If the well screen is above the water table, at least 6 in. of bentonite is placed above the sand filter and grout is filled in above it.

  Bentonite is available in either powder or pellet form from well drilling companies. Pellets are easier to use in the field. Fine pellets can be dropped directly down the annular space above the sand filter. If this zone is already saturated with water, the pellets will absorb water in place, swell tight, and seal off the sand filter from the annular space above. If the bentonite pellets are

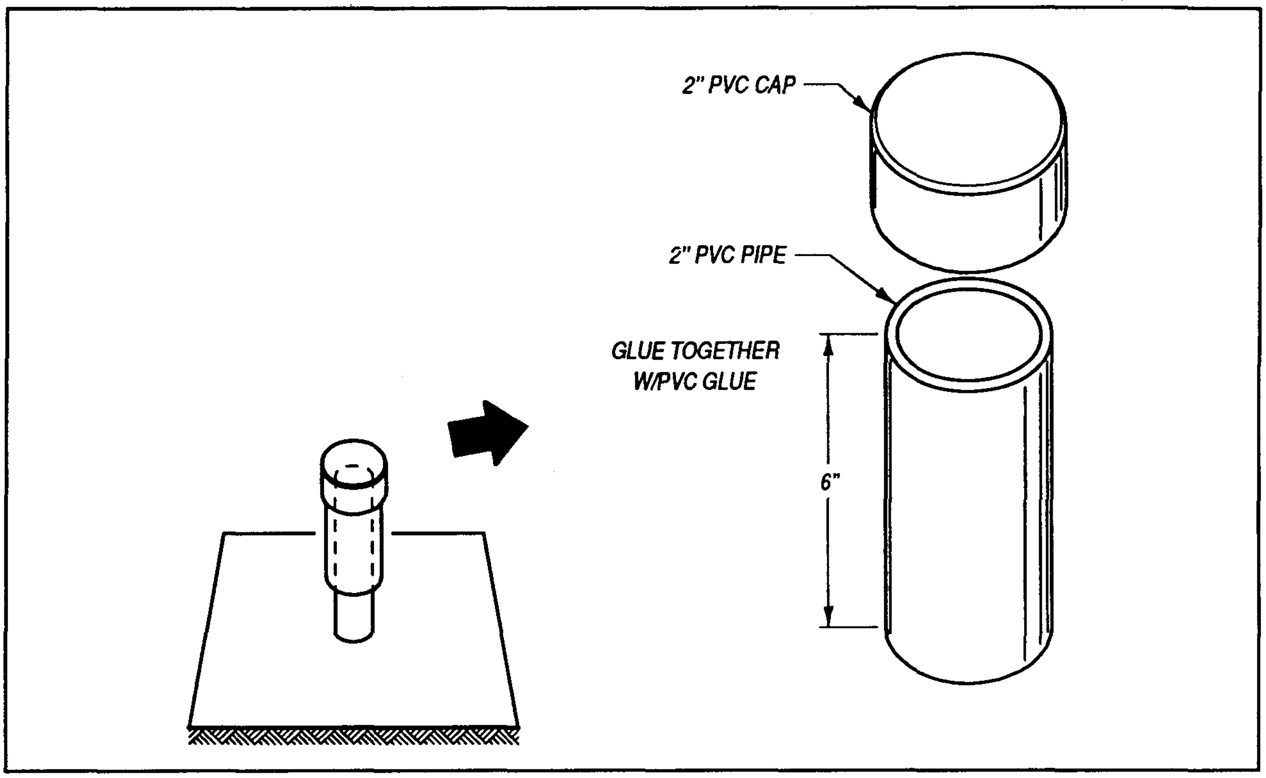

Figure 2. Homemade cap made of oversize PVC piping

dropped into a dry annular space it is necessary to drop water down, too, so the pellets can swell shut. The purpose of the bentonite collar is to prevent grout from flowing into the sand filter.

After the bentonite has been installed, grout is mixed and dropped down the remaining annular space up to the soil surface. The recipe for grout is 100 pounds of #2 Portland cement, 5 pounds of bentonite powder, and 7 gallons of water. The grout provides the primary protection from side flow down the riser because (1) it penetrates the surrounding soil matrix better than bentonite and (2) it does not crack during dry seasons.

- Sand is placed around the entry ports of the screen. Clean silica sand is commercially available from water-well supply houses in uniformly graded sizes. Sand that passes a 20 mesh screen and is retained by a 40 mesh screen (20-40 sand) can be successfully used with 0.010-in. well screen; finer sized 40-60 grade sand is appropriate for use with 0.006-in. screen. If available, the finer sand and screen should be used to pack instruments in dispersive soils with silt and fine silt loam textures.

  ASTM-5092-90 recommends that primary filter pack of known gradation be selected to have a 30% finer (d-30) grain size that is about 4 to 10 times greater than the 30% finer (d-30) grain size of the hydrologic unit being filtered. Use a number between four and six as the multiplier if the stratum is fine. This recommendation may not be achieved in clayey soils, in which case filter socks should be used.

- Filter socks are tubes of finely meshed fabric that can be slipped over the screened end of a well to filter out silt and clay particles that may be carried toward the pipe in flowing water. These should be used in conjunction with sand packs in highly dispersive soils. Filter socks are available from engineering and water-well supply houses. Results of multi-year studies indicate that geotechnical fabric may clog up with microbial growth. In long term projects, filter socks must be monitored.

- Protective concrete pads are often poured around the pipe at the ground surface. They serve two purposes: (1) if large enough, concrete pads can prevent run-off water from channeling down the sides of the pipe, and (2) in many states they are required on all water wells to protect sources of drinking water from contamination.

  Accurate ground-water monitoring requires that instruments be isolated from incursion of surface run-off down the sides of the pipe. A large sloped concrete pad (3 or more feet in diameter) will usually prevent run-off from collecting around the pipe and preferentially running down it. However, water channels can develop underneath hastily installed concrete pads. Poorly constructed concrete pads will crack as the soil underneath settles or heaves with shrink/swell and freeze/thaw cycles. Installation of a tamped and wetted bentonite sleeve around the pipe and proper mounding of soil around the base of the riser at the ground surface will prevent side-flow more effectively than an improperly constructed concrete seal.

  Some states require that all monitoring wells be isolated from surface flow with a concrete pad. This regulation is intended to protect drinking water sources from pollutants in surface run-off. State regulations should be observed at all sites despite the inconvenience of transporting materials to remote locations. A copy of the state's water well regulations must be obtained and proper forms for each pipe must be filed. For shallow instruments that are many meters above aquifers or aquifer recharge zones it is recommended to consult with the appropriate state agency for an exemption. Most of the time common sense will prevail and such pads may be omitted from the design of very shallow wells.

INSTALLATION OF SHALLOW MONITORING WELLS AND PIEZOMETERS:

- Shallow Monitoring Wells. Installation method is for 2-ft deep monitoring wells.

  Uses: Shallow monitoring wells may be used to determine when the shallow free-water surface is within depths required by jurisdictional wetland definitions. These depths have historically varied from 0.5 to 1.5 ft and are shallower than the shallowest slowly permeable zone in most soils. Therefore, 2-ft deep monitoring wells are sufficient to detect water tables in most soils if the only information needed is whether a jurisdictional wetland is present. To know how much the water table fluctuates during the year at least one deeper piezometer should be installed next to the shallow monitoring well. Deeper wells with 3 or 4 foot screens require that horizons have similar permeabilities.

  Construction: Shallow monitoring wells used for wetland jurisdictional determinations should have 1.0-1.5 ft of well screen. Enough riser should be added above the screen to allow 0.5 ft of riser below ground and 0.5 to 1.0 ft of riser above ground. The above-ground portion of the riser should be kept to a minimum to protect the surface seal from disruption during accidental jostling. A vented well point should be added to the bottom of the screen and a well cap to the top of the riser.

  The total length of the instrument will be approximately 3 ft: 1.5 ft of screen, 0.5 ft of riser below ground, 0.5 ft of riser above ground, and 0.5 ft of well point and cap. The well should be constructed of 1-in. ID PVC pipe with threaded joints unless water sampling or automatic monitoring devices require wider pipe.

Installation: A shallow monitoring well should be installed by (1) auguring a 2.5-ft deep hole in the ground with a 3-in. bucket auger, (2) placing 6 in. of silica sand in the bottom of the hole, (3) inserting the well into the hole with the vented well-point into but not through the sand, (4) pouring and tamping more of the same sand in the annular space around the screen -- this should be at least 6 in. below the ground surface, (5) pouring and wetting 2 in. of bentonite above the sand and (6) pouring grout to the ground surface. A final mound of grout prevents surface water from puddling around the pipe unless a concrete pad is required. Installation is illustrated in Figure 3.

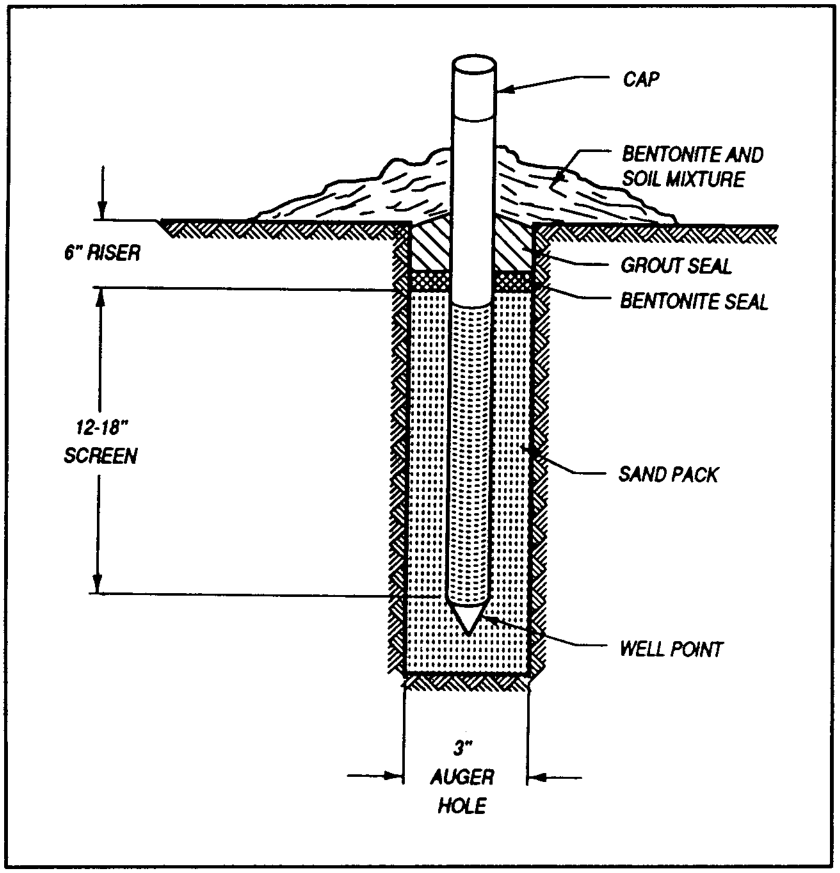

Figure 3. Shallow monitoring well

- Standard Piezometers. Installation method is for standard piezometers.

Uses: Standard piezometers are the preferred instrumentation for monitoring water tables. This method should be used whenever results may be published or litigated. Even in most jurisdictional studies involving shallow monitoring wells, a few standard piezometers should be installed around the project site to learn how deep the water table drops during the dry season.

Construction: Standard piezometers consist of 0.5-1.0 ft of screen, enough riser to extend above the ground, well cap, and vented well point. The total length of the piezometer will depend on the depth of the zone being monitored. Pipe diameter should be one inch unless sampling or monitoring instruments require wider pipe.

Installation: Installation of a standard piezometer entails (1) auguring a 3-in. diameter auger hole to a depth of 6 in. greater than the below-ground length of the piezometer; (2) dropping and tamping 6 in. of sand into the bottom of the augured hole; (3) inserting the well-point and pipe into the sand; (4) tamping sand around the length of the screen and 6 in. higher along the riser, (5a) if the sand filter is below the water table, pouring bentonite pellets into the annular space from the sand filter up to the water table, or (5b) if the sand filter is above the water table, pouring bentonite pellets at least 6 in. above the sand filter and wetting with water; and (6) pouring

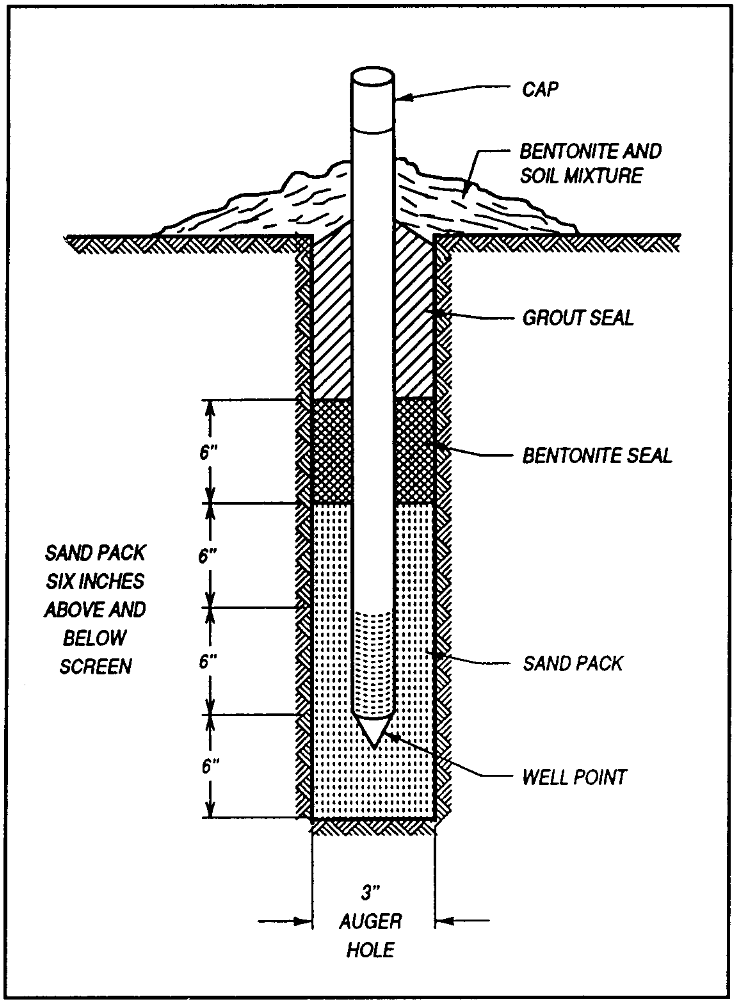

Figure 4. Standard piezometer

grout down the remaining annular space to the ground surface (Fig. 4).

The diameter of the auger hole should accommodate the pipe and an annular space of at least 1 in.; this will allow sufficient room to tamp in sand and pour bentonite without risking cavities in the sealant. The part of the hole that will be occupied by sand should be scarified if the soil is moist and smeared by the auger.

In deep sandy soils the bentonite and grout sleeves are not necessary because water flows through the entire soil matrix almost as quickly as down the sides of the pipe. The annular space around the riser is simply backfilled with sand that was removed during auguring. If the natural sand is fine enough to enter the slots of the piezometer, a sleeve of 20-40 grade sand should still be installed around the screen. If a less permeable layer is intercepted -- for instance, a spodic horizon -- that layer should be sealed with bentonite.

- Equipment Needed. Equipment needs will vary with depth and diameter of piezometers to be installed. The following is a list of equipment necessary for installation of shallow monitoring wells and standard piezometers to depth of 10 ft or shallower.

PVC well screen, riser, well points, and caps
bucket auger 2 in. wider than the OD of the pipe
auger extensions
pipe wrenches for auger extensions
tamping tool (0.5-in. thick lath 2 ft longer than the deepest well works well for wells up to 4 ft deep; 0.5-in. diameter metal pipe is necessary for deeper wells)
bentonite pellets
#2 Portland cement and bentonite powder (100/5 ratio)
bucket for mixing grout
water for grout and bentonite
silica sand
steel tape long enough to measure deepest hole
permanent marking pen to label pipes
concrete mix, water, wood forms, etc., for construction of concrete pads, if required

- Checking for Plugged Pipes. After the pipe has been installed it is necessary to assure that it is not plugged. For pipes installed above the water table fill the pipe with water and monitor rate of outflow; for pipes installed below the water table pump the pipes dry and monitor rate of inflow. If the screens are plugged one should re-install the pipes. This test should be performed every few months throughout the study.

READING WATER LEVELS: Numerous methods have been devised for reading water levels in shallow piezometers and wells. The simplest method is to mark a steel tape with a water-soluble marker and insert the tape to the bottom of the well. The only equipment needed with this method is the tape, marker, and a rag to wipe the tape dry after reading.

Other methods involve use of various devices at the end of a flexible tape. All suffer from the lesser accuracy obtained with a flexible tape rather than a rigid one. Most also suffer from inconvenience or complexity. Some of the variations are: (1) floating bobs on the end of a flexible tape (these must be calibrated to correct for length of the float and for displacement of water); (2) electric circuits that are completed when a junction makes contact with water; and (3) devices that click or splash when a flexible tape is dropped down the well (there is always uncertainty about the exact depth at which the noise was heard).

Water levels may also be monitored continuously with down-well transducers and remote recording devices. These cost around a thousand dollars per well but may be necessary for some study objectives. Automatic recording devices may pose special limitations on pipe diameter or construction, so the recording instrumentation should be investigated before pipe is bought. Because automatic devices may be re-used in many studies, cost estimates should be prorated over their expected life rather than assigned only to one study. If study objectives require frequent readings at remote sites an automatic recording device may be the only option available.

One method of reading water levels that should be avoided is insertion of a dowel stick down the pipe. Dowels displace enough water to give significantly false readings, particularly if the pipe has a narrow diameter and the dowel is inserted the entire length of the pipe. A steel tape also displaces water, but not enough to cause significant error.

When reading water levels height of the riser above the ground surface should be noted. Monitoring wells and piezometers may move as much as 3 in. in a season in clayey soils that undergo wet/dry or freeze/thaw cycles.

Frequency of reading will depend on study purposes. When determining consecutive days with water tables at a particular depth for wetland delineation purposes, daily readings may be necessary once the "growing season" starts. Daily and even hourly readings may be necessary to monitor tidally influenced wetlands. Longer term studies are usually adequately served with biweekly readings during most of the year and weekly readings during periods of water-table rise or draw-down. Long breaks between readings may cause ephemeral fluctuations due to intense storms or floods to be missed. If the study is important enough to be published or litigated, readings should be frequent and regular.

SOURCES OF ERROR: The following are significant sources of error with piezometers and monitoring wells: (1) side-flow down the riser, (2) plugged screens, (3) movement of pipes due to shrink/swell and freeze/thaw cycles, (4) water displacement during reading, (5) infrequent readings, (6) incorrect instrumentation, (7) pipes of too large a diameter, (8) faulty caps, and (9) vandalism.

- Side Flow. Erroneously high water heads can be recorded in piezometers and shallow monitoring wells if water is conducted to the screen faster than it normally would be through the soil. The most common source of this water is surface run-off channelled down the sides of the riser. It is critical that wells and piezometers fit snugly into the ground and that a collar of soil be mounded and tamped around the base of the pipe at the ground surface. This is the primary reason that the standard piezometer installation described here is preferred over simply driving the pipe into the ground; bentonite and grout seals are more secure than natural soil contacts along driven pipe.

  With piezometers, an additional source of error is subsurface water conducted to the pipe via cracks, root channels, or animal burrows. These problems will not be significant in all soils. When present, the only protection is an adequate sleeve of bentonite and grout around the riser.

  In montmorillonitic soils with high shrink-swell potential, one may never be able to eliminate cracks. In this case it may be necessary to auger soil samples from depth and determine water contents gravimetrically throughout the year. Such gravimetric determinations should certainly be made whenever false readings in piezometers are suspected.

- Plugged Screens. The slots or holes in screens may plug up, particularly in dispersive soils that are saturated for long periods of time. Algal growth can also plug up screens of instruments installed at biologically active depths. Plugged screens can give artificially dry readings during wet periods and artificially wet readings during dry periods. They will impede water flow so that fluctuating water tables can be missed even with frequent readings.

  Plugging of screens is most easily prevented by using an appropriately sized sand filter. One can check for such plugging by pumping wells dry on a regular basis and noting if they fill back up again.

  If shallow monitoring wells plug up, they should be re-installed. Deeper piezometers may be unplugged by pumping the wells dry several times and discarding the muddy water pumped out. If they continue to plug, they should be re-installed with 40-60 grade sand and 0.006-in. screen or with a filter sock.

- Movement of Pipes. Shallow pipes move much more than one would expect. Concrete collars can be lifted several inches above the ground in soils with clayey texture. This movement is caused by soil expansion during wetting or freezing. There is little one can do to prevent this, but one should monitor such movement by noting the height of the pipe out of the ground when reading water table depths.

  Pipes that move a lot and experience inundation as well probably no longer fit snugly in the ground and therefore experience side-flow down the riser. Gravimetric water contents should be checked whenever one suspects false readings due to side flow. If these problems persist, piezometers should be re-installed.

- Water Displacement. As mentioned previously, water levels in wells should not be read by inserting a dowel stick down the pipe. The dowel will displace its volume in water and thereby give an artificially high reading. A marked steel tape should be used instead.

- Infrequent Readings. A common source of error in many long-term studies is missed or postponed readings. Before the study is started one should arrange for sufficient help to make readings on schedule and frequently enough to answer study questions. It is all too easy for professionals with many other responsibilities to delay a trip to the field because of intruding obligations. Yet, gaps in a data set will call an entire study into question. If budgets allow, automatic recorders may solve the problem.

- Incorrect Instrumentation. Piezometers are preferable to shallow monitoring wells for most questions more complicated than simple presence or absence of water tables in the rooting zone. Water levels in monitoring wells are composites of the hydrologic head at all depths intercepted by the well screen. Consequently, perched water tables will usually be misinterpreted if monitoring wells penetrate the drier substratum beneath.

  Readings from improperly placed piezometers can also be misinterpreted. Piezometers should not be placed at uniform and arbitrary depths without reference to soil horizon differences. Piezometers placed at arbitrary depths are likely to straddle horizon boundaries or entirely miss highly permeable horizons with significant subsurface flow.

- Large-Diameter Wells. Piezometers and wells should be as narrow as practical. The wider the pipe, the greater the volume of water that has to move in and out of it in response to changes in hydraulic head. Consequently, a large-volume monitoring well will respond more sluggishly than a small-volume well. This is more critical in soils with low permeability and for studies that require monitoring several times a week or shortly after major precipitation events.

  Most wells can be successfully constructed from 1 or 1.25 in. pipe. Use of 4 or 6 in. pipe should be avoided unless study conditions require the larger pipe. An excessively large annular space should also be avoided, for the same reasons.

- Faulty Caps. Commercially manufactured caps often fit too tightly on PVC riser, necessitating excessive force to remove them. The resultant jostling can disrupt the seal between the pipe and the sealant, allowing water flow along the side of the pipe. To avoid this, threaded caps -- if used at all -- should be screwed on the pipe loosely. Avoid caps made of materials that deteriorate and break in sunlight or frost, can be nudged off by animals, or blown off in the wind. Most such problems can be alleviated by use of home-made caps constructed as described in Figure 2.

- Vandalism. Often vandalism cannot be avoided. Three approaches to the problem are (1) to hide the wells, (2) to shield them, and (3) to post them and request they not be disturbed. Simple signs stating "Ground-water pipes: please do not disturb" have been used successfully. In some communities it may be better to hide the pipes. Padlocks may keep out the curious. A second and larger pipe surrounding the above-ground portion of the monitoring well may offer protection against gunshot. Still, pipes probably cannot be protected from the malicious. Extra equipment should be bought at the beginning of a project so that vandalized wells can be replaced.

INTERPRETING RESULTS: As mentioned previously, data from shallow monitoring wells are ambiguous unless the well is very shallow (2 ft or less), or the soil is highly permeable or unstratified. A 4-ft deep well that traverses a profile of A-E-Bt-C is likely to miss the slightly perched water table that rests on top of the Bt and in the E. The most permeable horizon contributes the most water to a water well. If the bottom of the well intercepts an unsaturated horizon of higher permeability, then water can actually be wicked away from the well.

Piezometric data can also be confusing unless one is familiar with principles of water flow. If water is static in unstratified soil, water levels in all piezometers should be the same (Fig. 5). However, if

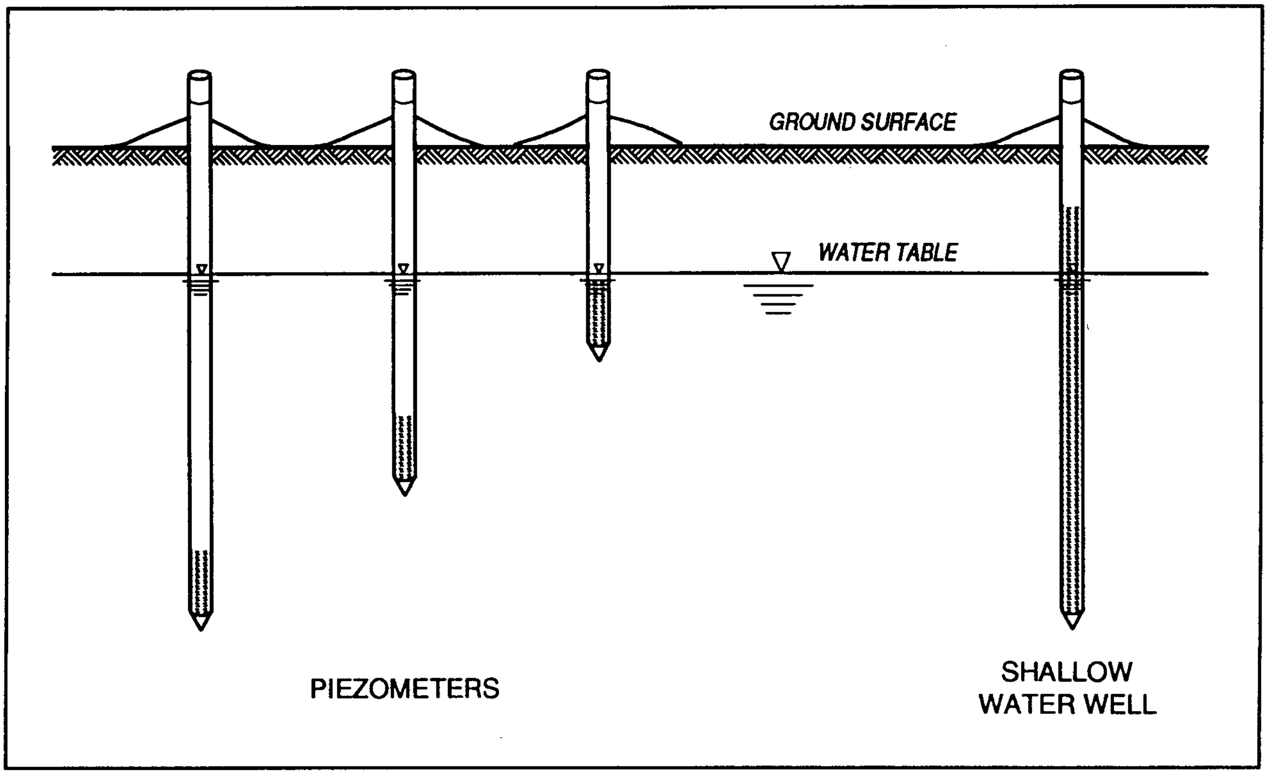

Figure 5. Instruments in unstratified materials with static water-table

differentially permeable strata are present or if water is moving up or down the soil profile, then piezometers will record different water levels at different depths.

A perched water table can be inferred from higher piezometric levels in the A or E horizon than the C (Fig. 6). For soils of uniform permeability, downward water movement (aquifer recharge) can be inferred from higher piezometric levels high in the soil and lower piezometric levels low in the soil (Fig. 7). Upward water movement (aquifer discharge) can be inferred from lower levels high in the soil and higher levels low in the soil (Fig. 8). Water moves from a zone of high pressure to a zone of low pressure, even against gravity, if the pressures are great enough. Proper interpretation of data requires some knowledge of soil horizonation and likely water sources.

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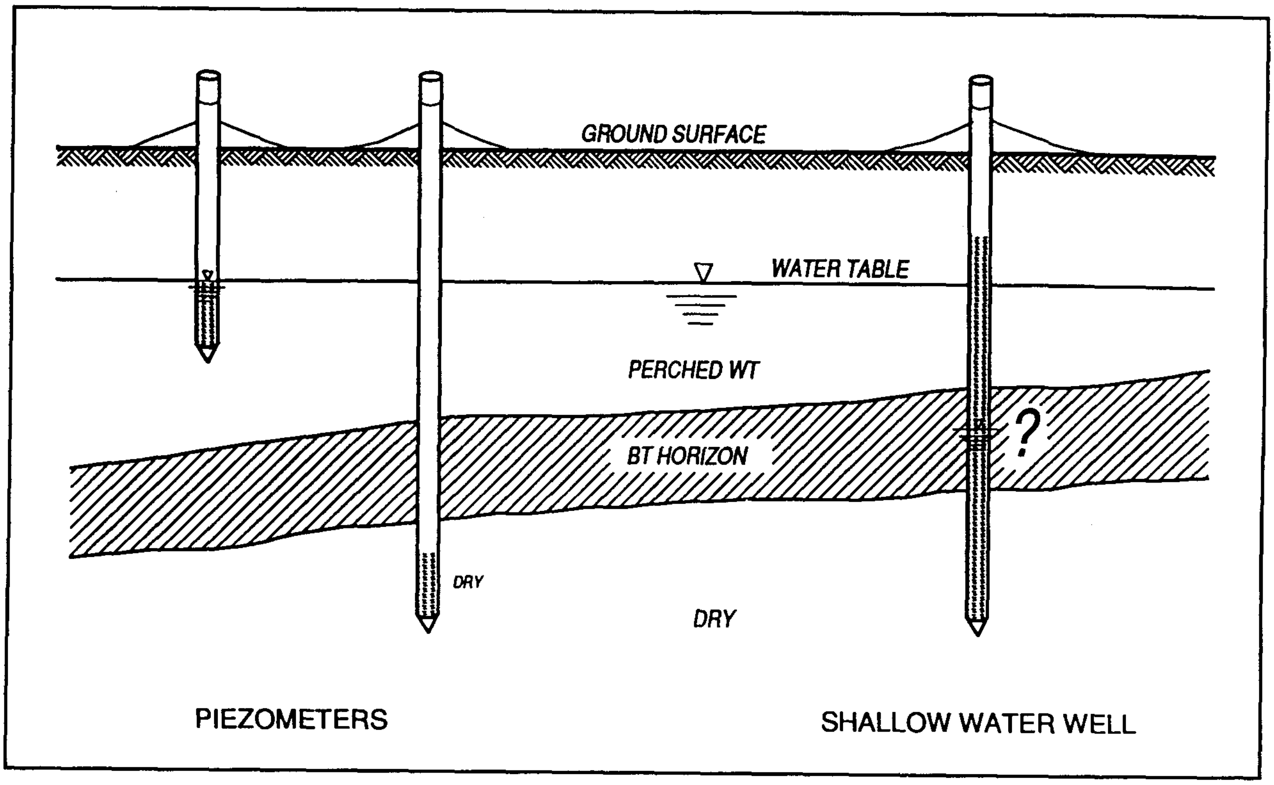

Figure 6. Monitoring instruments in stratified materials with perched water-table

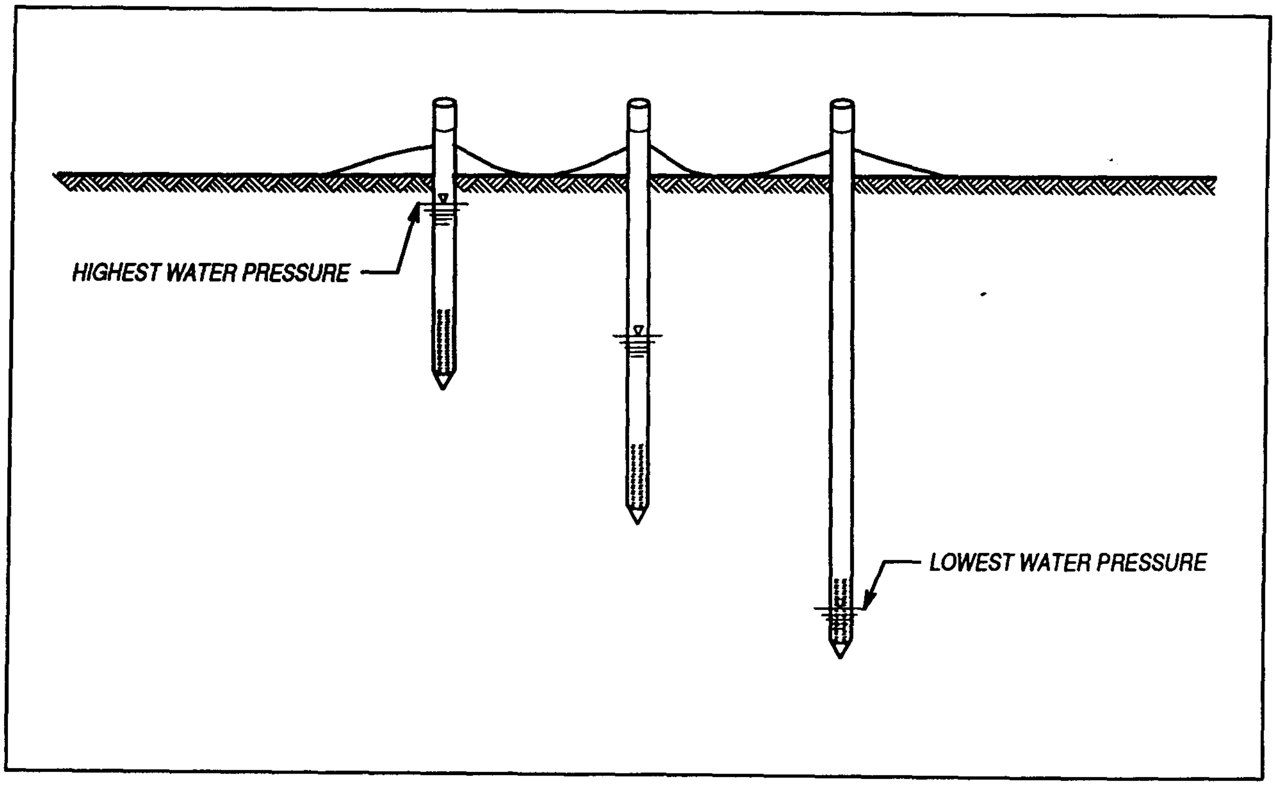

Figure 7. Recharge system with water flowing downward

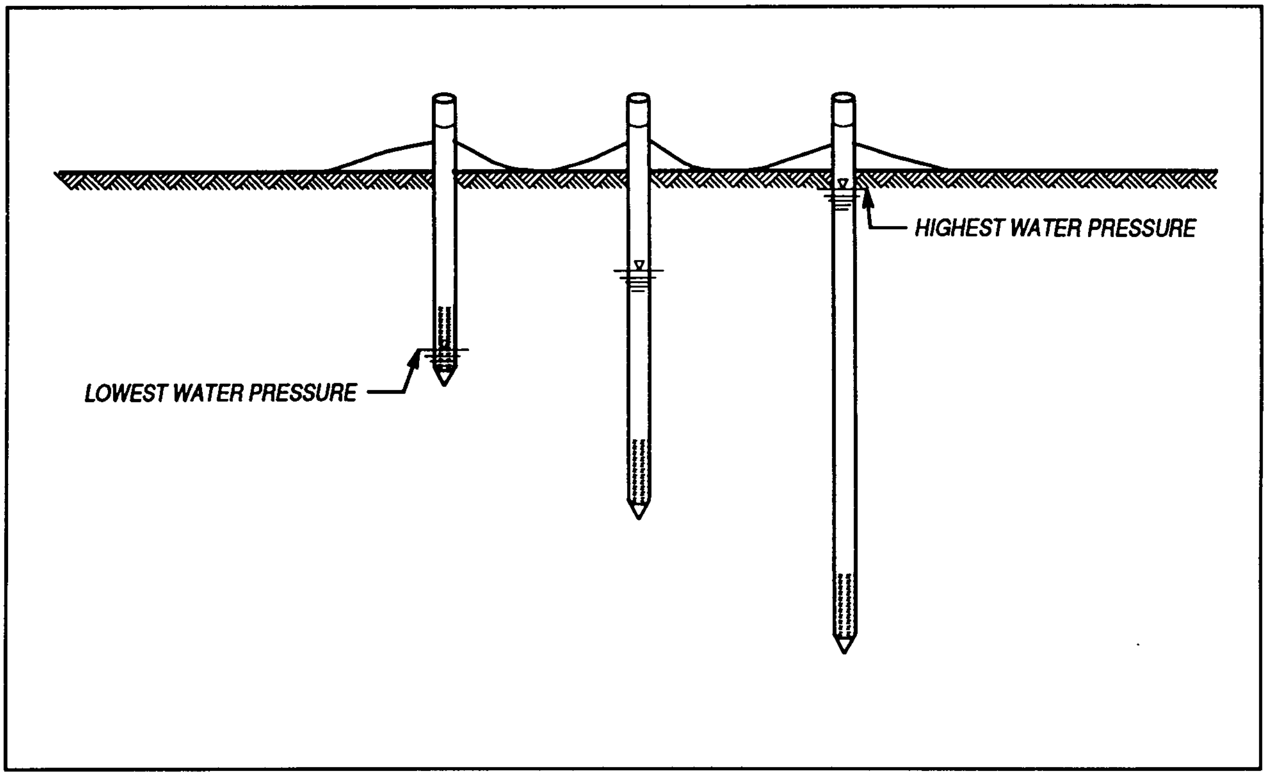

Figure 8. Discharge system with water flowing upward

US Environmental Protection Agency. 1975. Manual of Water Well Construction Practices, Office of Water Supply, EPA-570/9-75-001.

POINT OF CONTACT FOR ADDITIONAL INFORMATION: Steven W. Sprecher, USAE Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, Phone: (601) 634-3957, author.

WRP Technical Note HY-IA-5.1
August 1993

GeoSHED Software for Wetlands Drainage Analysis

PURPOSE: This technical note documents recent software developments in automated drainage basin analysis and describes how the tools can be used in wetland environments.

BACKGROUND: A detailed knowledge of wetland hydrology is perhaps the first, if not the most important, aspect of wetland behavior that the wetland scientist must understand prior to implementing wetland improvements or designing new wetlands. Hydrologic inputs define the frequency and depth of inundation of the wetland which in turn defines habitability for various plants and wildlife. In fact, wetlands are defined and typed by the frequency in which they are inundated. Since there are a wide range of wetland types ranging from alpine meadows to tidal marshes, there is a need for generalized tools for studying hydrologic behavior. The tools must be able to quantify runoff from rainfall, route the flow through stream networks within the wetland, and account for groundwater sources and losses. Unfortunately, the requirements for studying each process require different technical approaches and models.

In the early stages of the WRP, tools are being developed that address each aspect of the hydrologic cycle separately with an interest in improving existing tools and making them easy to apply to wetland applications. Three categories are being addressed as distinct entities. They include runoff calculations using such models as HEC-1, calculations of shallow water flow using two-dimensional models such as the TABS system, and groundwater models to determine the effect of groundwater on the wetland water budget. This technical note addresses the first category but ensuing technical notes will address the latter two. Each of the categories will be addressed with consistent data structures to allow them to be coupled when they are mature and when integrated solutions are required.

EXISTING TOOLS: A wide variety of free surface and groundwater tools are available for meaningful hydrologic analyses. The Corps of Engineers and other federal agencies have many computer codes that can determine surface runoff from rainfall information with some degree of confidence. Perhaps the most widely used code is HEC-1 which was written by the Hydrologic Engineering Center (HEC) in Davis, California. This model is well-supported by HEC and there is good documentation including a user's manual (HEC, 1990).

Unfortunately, HEC-1 is time-consuming to use by other than professional hydrologists. Typically, the most time-consuming tasks in setting up a hydrologic simulation involve discretizing the watershed, defining the major streams and sub-basins, calculating drainage areas and other pertinent hydrologic statistics, and writing out this information in a form expected by the hydrologic models. Automated software would minimize the time and number of errors caused by manual watershed analyses. This would result in widespread use of good hydrologic models with greater detail and accuracy given to each hydrologic application.

AUTOMATED INTERFACE: A graphically-based hydrologic pre-processor program (GeoSHED), that was originally developed for generic surface water applications (Jones, et al, 1990), is currently being used to automate each of the tasks discussed above in wetland applications. GeoSHED employs Triangulated Irregular Networks (TINs) to define the topography and calculate vital hydrologic statistics. A TIN is a set of data points that are connected by irregular triangles that together describe an irregular surface (Figure 1). TIN's are created by inputting digitized data, either from digital topographic maps or from manually digitized data, and triangulating the points. Once the TIN is created, a continuous surface is modeled by interpolating between the corners of the triangles.

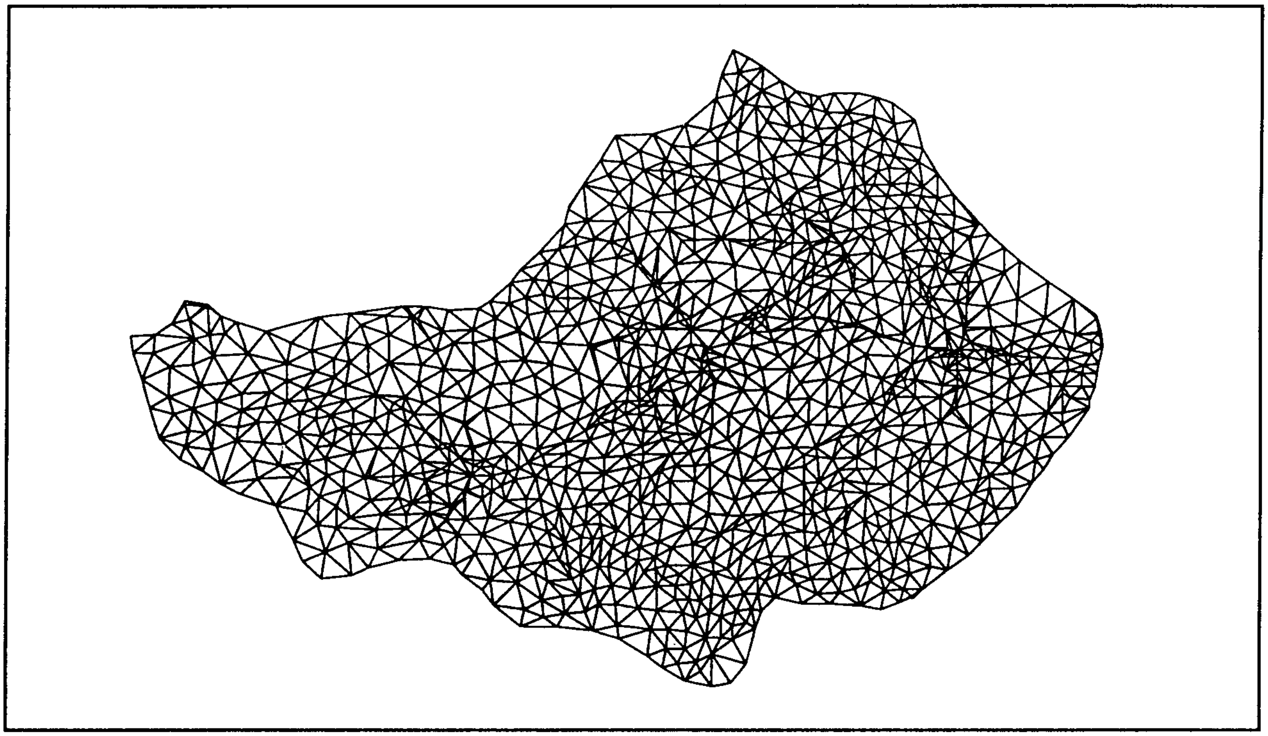

Figure 1. Triangulated Irregular Network (TIN) of a watershed

After the surface is modeled, GeoSHED automatically defines the dominant streams and flow paths on the screen (Figures 2 and 3). In Figure 3, flow path lines are drawn on the screen from the centroid of each triangle down slope in the direction of steepest descent. With the primary streams and flow paths defined, GeoSHED calculates the contributing drainage area to each of the user-defined stream junctions. The drainage areas for each sub-basin along with critical hydrologic statistics for each sub-basin can be displayed (Figure 4). Previously, it was necessary to planimeter each sub-basin manually and type the data into an input file. GeoSHED automatically writes out the data in a form that HEC-1 accepts.

The developed software eliminates most of the tedious tasks in assembling data input files for hydrologic simulations. To run hydrologic simulations of watersheds, all that is needed is a digitized data set with x-, y-, and z-coordinates, the GeoSHED software, and a copy of HEC-1. HEC-1 is available from the Hydrologic Engineering Center and GeoSHED is available from the U.S. Army Engineer Waterways Experiment Station.

COMPUTER INFORMATION: The GeoSHED software runs on most UNIX workstations using X-Windows graphics. It also runs on DOS-based personal computers using WINDOWS 3.1. A user's manual and installation guide are available.

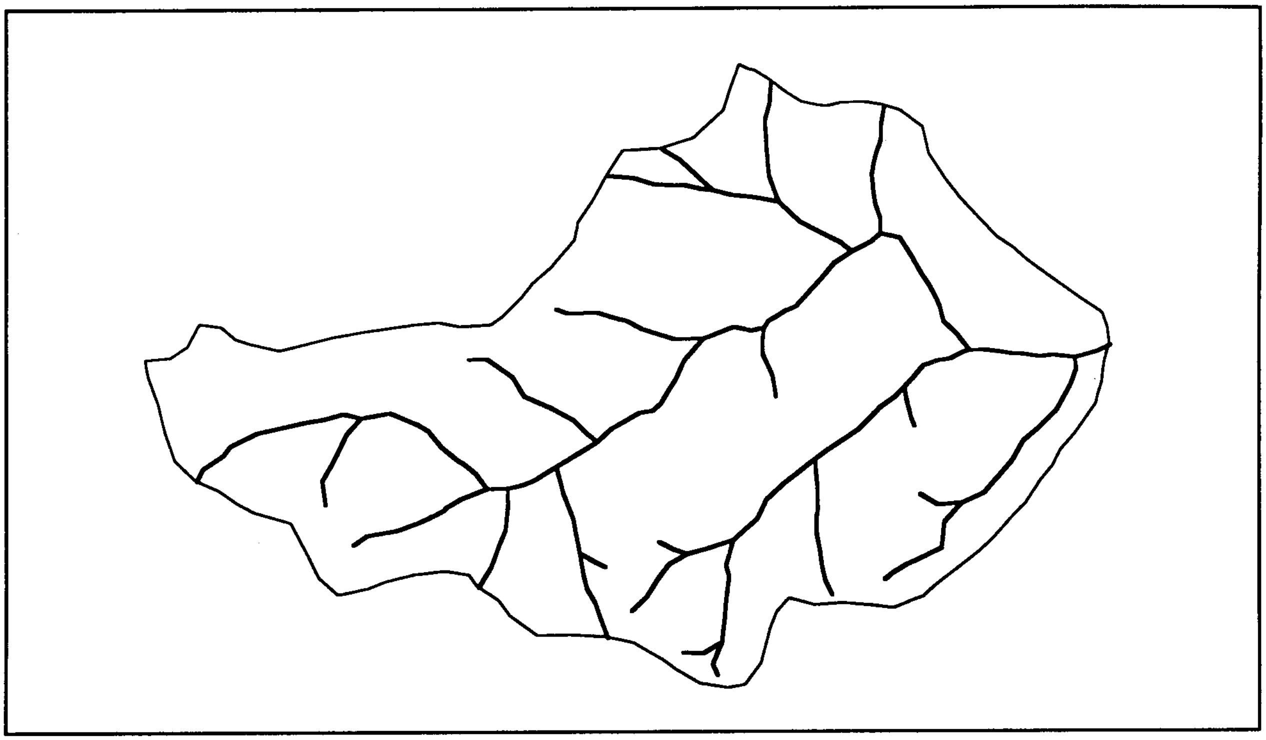

Figure 2. Primary streams defined from the TIN

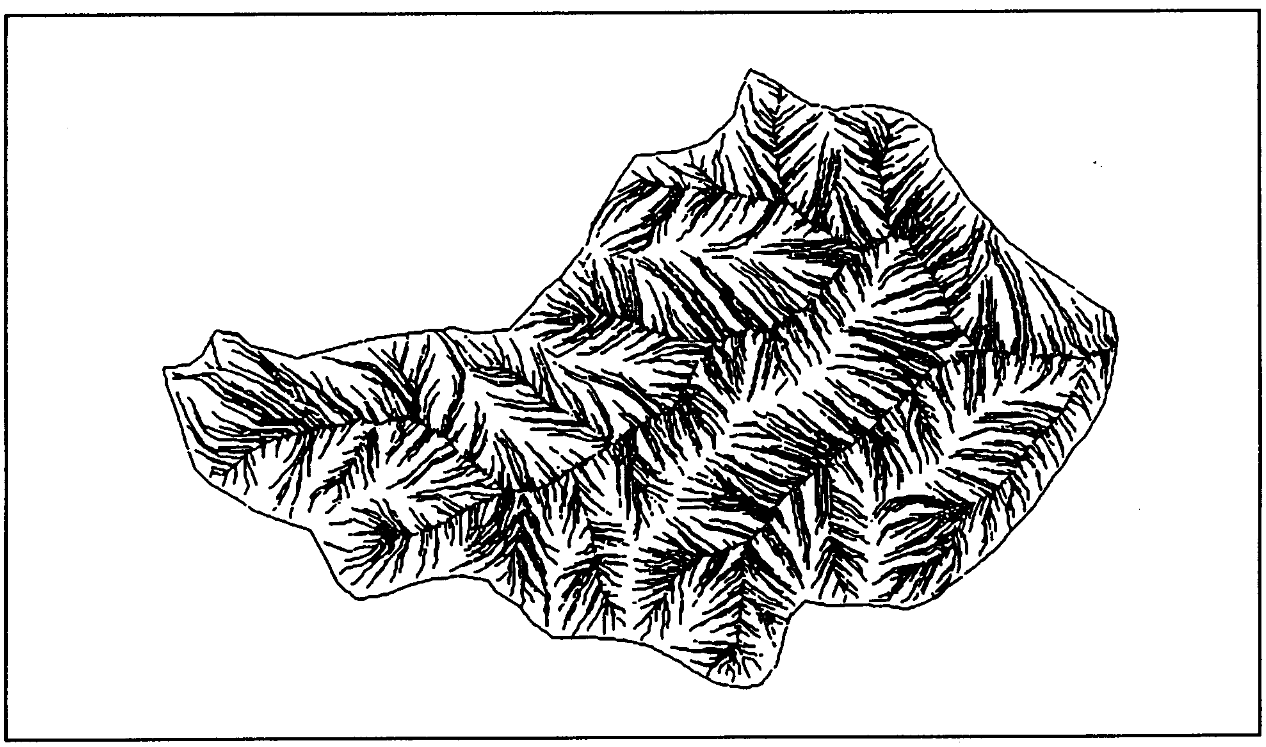

Figure 3. Overland Flow Paths defined by the TIN

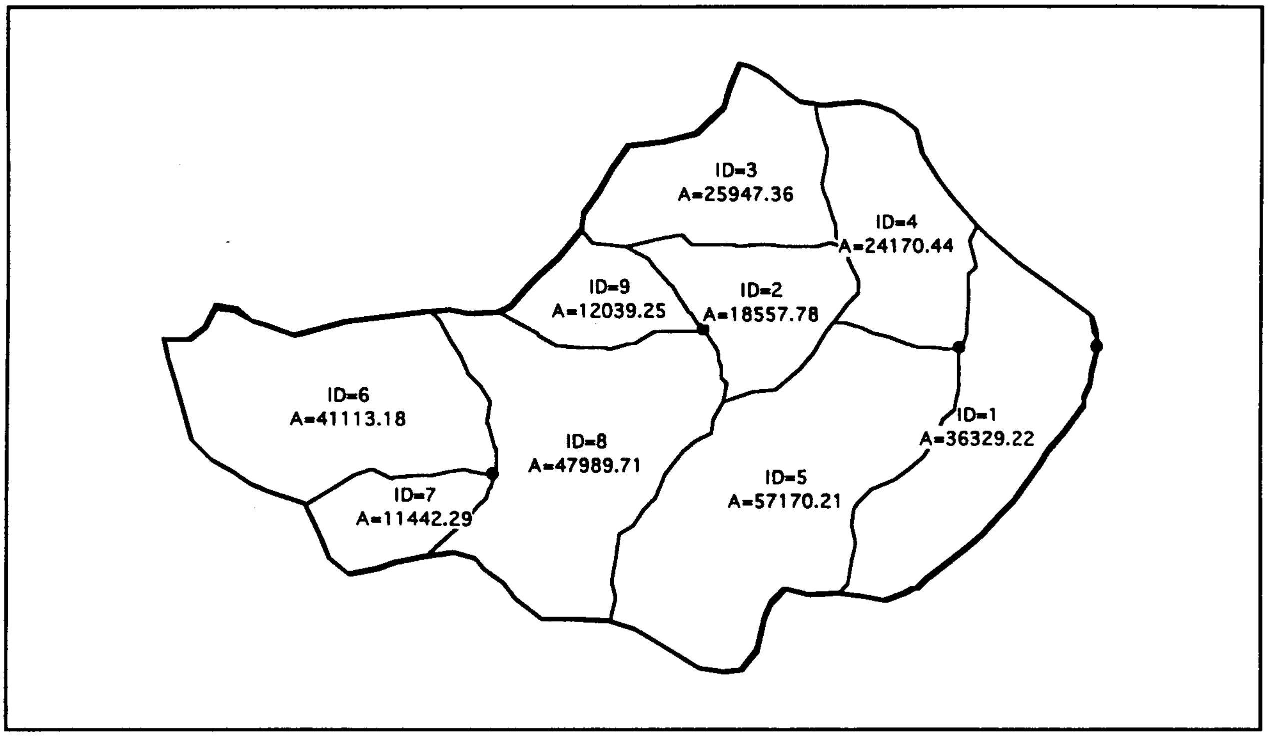

Figure 4. Drainage Areas delineated for each sub-basin using the TIN

The GeoSHED software was written by the Engineering Computer Graphics Laboratory of Brigham Young University in Provo, Utah, in cooperation with the Hydraulics Laboratory at WES and is copyright to Brigham Young University. A limited government license allows Corps office use of software supplied through WES. Other than Corps users may obtain the software from Brigham Young University, (801) 378-5713.

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WRP Technical Note HY-RS-3.1
August 1993

Hydrology and Hydraulic Design Criteria for the Creation and Restoration of Wetlands

PURPOSE: Hydrology is generally accepted as the single most important factor governing the successful establishment and maintenance of specific wetlands types and wetland processes. Long before the study of wetlands was a separate field of science, early scholars recognized the importance of hydrology in the establishment of wetland types and the attainment of wetland functions. Still, many wetland establishment or restoration projects fail because the proper hydrology and hydraulics needed to meet the project goals were not attained.

Failure to establish the correct hydrology can result in a different type of wetland than desired or mandated, no wetland, or a failure to achieve desired functions and the establishment of undesirable flora and fauna. This technical note provides hydrology and hydraulics informational background for four basic wetland types along with important considerations in developing functional design.

BASIC WETLAND TYPES: In the hydrogeomorphic classification for wetlands (Brinson, 1993), there are four basic wetland types; riparian (or riverine), fringe, depressional, and peatland. These are defined by geomorphic setting; however each has it's own unique hydrology. In addition, each type naturally lends itself to certain functions.

- Riparian. Riparian wetlands are those found along rivers and in river floodplains or basins. Because of their close association with rivers, the greatest source of water for these wetlands is from riverine flood flows usually following flooding of the associated river. Although flooding may be infrequent, flooding frequency and duration will largely determine the type of vegetation that occurs.

  A southern bottomland hardwood (BLH) forest or swamp, located along a river or stream, is a good example of how important flooding frequency is in relation to vegetative composition. Flooding tolerances of some common representative BLH trees are listed in Table 1.

Table 1.[1] Flooding Tolerance of Common BLH Tree Species

Cypress/Tupelo	6-8 months
Overcup Oak/Red Maple	4-6 months
Pin Oak/Sweet Gum	1-6 months
Cherrybark Oak/Willow Oak	1-3 months

[1] Fredrickson, L. H., and M. E. Heitmeyer, 1988. Waterfowl Use of Forested Wetlands of the Southern United States: An Overview. Chapter 22 in Waterfowl in Winter. 1988 University of Minnesota. Milton W. Weller ed. University of Minnesota Press, Minneapolis, MN.

These plants cannot withstand flooding in excess of the listed values. If the hydrology of a river or stream in the BLH forest is changed by either damming the stream or changing land use around the stream and affecting runoff, plant composition in the forest will also change. In mildly affected systems this may shift the dominant tree species from pin oak to overcup oak. Yet, if the hydrology is drastically altered, as in the case of introducing dams or other control structures to hold nearly constant water levels, then the entire forest can be lost. Restoration of such a forest will be impossible, unless the appropriate hydrology is restored.

Riparian areas naturally function to attenuate flood flows. Peak flows are diminished as the water spreads out over the flood plain. As flood waters recede, the floodplain gradually releases its water. This results in flatter hydrographs and less downstream flooding. Likewise, most riparian wetlands are very effective sediment traps. Fast moving sediment laden flood flows slow down over the vegetated floodplain and drop a large portion of the sediment load. The removal of sediment also removes associated nutrients and toxicants such as herbicides and pesticides that typically attach themselves to the suspended sediment, resulting in improved downstream water quality.

Riparian areas tend to be sites for groundwater recharge during flood flows and sites for groundwater discharge during low river flows. Because of the normal pattern of flooding and sedimentation deposition in this type of wetland, groundwater discharge or recharge usually are minor components of the total water balance. Accumulated, fine organic sediments tend to seal the bottom of riparian areas preventing much interaction with underlying groundwater. In western areas, where sediments may be largely inorganic, the riparian wetland water balance may have a large groundwater component.

Many riparian areas produce large quantities of organic matter such as annual wetland plants or leaf litter. During flooding, this organic matter is transported to downstream waters by receding flood flows. This ability of wetlands to produce and export organic carbon is often referred to as the production export function.

- Fringe. Fringe wetlands are located along the edges of larger surface water bodies such as oceans or lakes. The fringe wetland is generally found within the fluctuation zone of rising and falling water levels from the main body of water. These wetlands may be in the tidal region of an estuary, between mean high and mean low water, along the edges of a large lake subject to wind induced seiches, or within the fluctuation zone of a reservoir where water level changes may be caused by the operation of the reservoir.

  As with riparian wetlands, the hydrology of fringe wetlands is dominated by the larger source of water, in this case the lake, reservoir, estuary, or ocean. Direct inputs into the wetland system from rainfall, surface flows and groundwater interaction are subordinate influences. Viable wetland plant species will also be controlled by the larger source of water.

  In estuaries, there is typically a predictable sinusoidal rise and fall of water due to rising and falling tides. In this environment, spartina marshes tend to dominate the landscape, occurring in the region between mean high and mean low water. There is predictable daily wetting and drying of the land that is necessary for the establishment of the salt marsh.

  A combination of wind- and gravity-induced water movement can set up a sinusoidal movement of water in a lake, a process called a seiche. Large fresh water lakes with long fetches, are inclined to wind-induced seiching. A strong wind applied to a long fetch will pile up water on the downwind side of the lake. This causes a hydraulic gradient across the lake. As the wind subsides, the force of gravity will cause the water to move back toward the other side of the lake, which now has a lower head. Since the shoreline of the lake is exposed to a similar, although less uniform or predictable water regime as the estuary, it is capable of supporting freshwater spartina and bulrush marshes.

Most reservoirs constructed by the U.S. Army Corps of Engineers (USACE) are used for flood control and water supply. To accomplish both these goals most reservoirs have operating (rule) curves similar to the one presented in Figure 1, for Grenada Lake in northern Mississippi.

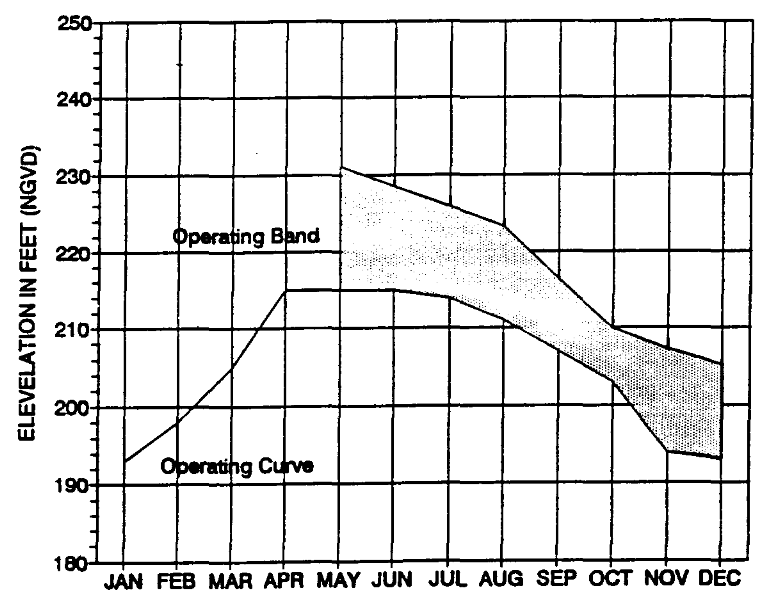

Figure 1. Grenada Lake rule curve*

* (from United States Army Corps of Engineers (USACE), Vicksburg District, 1989. Standing Instructions to the Project Manager for Water Control, Grenada Lake, Yazoo Basin)

As shown in the figure, the typical pattern of operation for the lake is to draw down the water level to conservation pool in late winter allowing heavy spring flows to be captured to prevent flooding. Water gradually released during the growing season provides water for irrigation. This type of operation exposes expansive mudflats on the lake floor and also provides an opportunity to establish large vegetated wetlands on the land lying between flood stage and conservation stage. However, because of the timing and magnitude of the water level fluctuations, establishing wetland vegetation in these areas is difficult.

The dominating hydrology of fringe wetlands is naturally suited for several functions. Fringe wetlands provide shoreline stabilization since the vegetation damps the magnitude of waves and currents. Similarly, this damping motion tends to reduce resuspension of sediments, improving water clarity and quality. If freshwater inflows must first pass through fringe wetlands before entering the lake or estuary, then significant sediment removal and water quality improvements can occur. The organic products of fringe wetlands are continually transported to the larger body of water. This increases the net productivity of the larger water body. Likewise, the fringe wetland can use the larger body of water as a source of nutrients, increasing the productivity of the wetland. Fringe wetlands also provide an area for flood attenuation.

- Depressional. Depressional wetlands, unlike riparian and fringe wetlands, are a more self-contained system, with their own hydrology. Depressional wetlands occur in geologic land depressions. They can form on either steeply or mildly sloping landscapes, and often form at the junction of steep and mild slopes. Depressional wetlands can have one or more inlets and outlets or no inlet or outlet, commonly the case with prairie potholes. Because of this morphology, depressional wetlands depend on a variety of water sources.

  Prairie potholes occur in the plains states of North Dakota, South Dakota, Nebraska, etc. Since prairie potholes have no inlet or outlet, the hydrology of these systems is dominated by rainfall and evaporation. Prairie potholes typically occur in semi-arid regions, and therefore are dry most of the year. The potholes tend to fill during early summer rains. Some systems with a link to groundwater may fill during spring thaw. The vegetation in these systems has adapted to this hydrology and flourishes during wetting cycles, dying off and becoming dormant during the long, dry period.

  Depressional wetlands with inlets and outlets are very similar in hydrology and hydraulics to reservoirs. These wetlands occur in every climate and in every region of the country. The hydrology of each wetland is unique. This is probably the most frequently constructed type of wetland; and typically the goal of these construction projects is to create a freshwater marsh or wet meadow. The success of such projects hinges on establishing the proper hydrology for the plant species selected. Any number of water sources, runoff, groundwater, rainfall, and flood flows may be used. The only requirement is that the proper water budget and hydroperiod, meaning the duration of wetting, be established.

  Because of the amorphous quality of the hydrology for depressional wetlands, they can be used for a variety of functions and can often be driven to perform certain functions by altering the current hydrology. Isolated prairie potholes provide excellent breeding habitat for migratory waterfowl. However, due to their isolated nature, these wetlands usually do not perform hydrologic functions. They may function as a source of groundwater recharge, but this is typically insignificant due to their small size. Depressional wetlands with inlets and outlets, however, often perform many of the same functions as riverine and fringe wetlands. They can provide for flood attenuation, sediment retention, water quality improvements, and net production export to downstream water bodies. The type of hydrology present in the individual depressional wetland will determine if and to what degree it performs any or all of these functions. Particular functions can be achieved by altering the wetland hydrology.

- Peatland. Peatlands, often referred to as bogs or fens, are depressional wetlands in a special geomorphic setting, with special hydrology and thus, special vegetative and chemical composition. Peatlands are formed in regions of the world that have a water surplus. The water to most peatlands is provided by precipitation. However, peatlands usually occur where the water table is high and in contact with the peatland, even during dry conditions. This causes the peatland to be continually wet, allowing for the formation of peat producing mosses and trees.

  Generally, peatlands have little or no surface water component. Peatlands tend to be nutrient poor, and the water tends to be acidic, a factor affecting the vegetation and characteristics of this type of wetland.

As peat accumulates in the depression where the wetland has formed, the peatland may continue to grow and expand beyond its original boundaries. Peatlands may grow into other peatlands, forming huge complexes.

Because peatlands occur in such specific hydrologic conditions, they are not well suited for typical hydrologic and related water quality functions. Though peat is a highly marketable item in some regions of the world, the construction or restoration of a peatland would most likely be done for aesthetic or specific wildlife habitat purposes.

SPECIAL HYDRAULIC CONDITIONS OF WETLANDS: Although much of what is known about hydraulics is directly applicable to wetlands there are some characteristics of wetlands that require special consideration. Two of the most important issues are briefly discussed below.

- Shallow Water Depths. Wetlands, by definition, are shallow vegetated bodies of water. Most wetlands are one meter deep or less. This shallow water depth has the effect of increased frictional resistance to flow.

- Aquatic Vegetation. The presence of aquatic vegetation in a wetland increases the frictional resistance to flow. Because of the occurrence of very thick vegetation, this effect can be dramatic, producing roughness coefficients far exceeding any values found in typical hydraulic references.

  In addition, the presence of emergent aquatic vegetation has the effect of redistributing the frictional resistance to flow all along the water column, thus redefining the velocity gradients. Because of this effect, friction factors are no longer constant, and tend to decrease with increased depth. This effect is plant species and density dependent so that flow resistance changes during the year as plants develop and then die, and, on a larger time scale, with species succession. Shih and Rahi (1982) determined that the calculated Manning's roughness coefficient for a subtropical marsh varied from 0.16 to 0.55 over a depth of only 65 to 40 cm, and that the coefficient increased by a factor of three over the six month period from June to November. In addition, flow in wetlands is frequently in the transition zone between laminar and turbulent flow (Kadlec 1990). Because of these and other complications, simple application of flow equations such as Manning's equation will not yield valid results and more detailed analysis is required.

CONCLUSIONS: Before beginning a wetland establishment or restoration project, it is necessary to understand the four basic geomorphic wetland types and the accompanying hydrology and hydraulics, as well as the functions that each type can typically achieve. Next, the planner should closely study the geomorphology and hydrology of available sites. Hydrology can be determined by either collecting field data or conducting hydrologic model studies of the area.

With this knowledge, the planner can make realistic determinations as to the possible wetland types and functions that can be established. Understanding of wetland hydrology and related functions is essential in accomplishing successful restoration projects and avoiding undesirable results and consequences. Designing engineers should be aware of special considerations in wetland hydraulics and make compensations to account for the differences between wetlands and open channel or reservoir hydraulics.

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